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Estimation Of Basic And Mission Benefit Of Condition-Based Maintenance Deployment In HUMS Equipped AH-64 Aircraft Using NLP And Regression Analysis

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ESTIMATION OF BASIC AND MISSION BENEFIT OF CONDITION-BASED
MAINTENANCE DEPLOYMENT IN HUMS EQUIPPED AH-64 AIRCRAFT USING
NLP AND REGRESSION ANALYSIS

by

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For the Degree of Doctor of Philosophy in

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2016

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DEDICATION

To my beloved parents Akhteruzzaman Bhuiyan and Shahanaaz Parvin, and my wonderful husband Junaed Bin Halim. I am truly blessed to have these three individuals in my life.

Thank you for motivating me to pursue this path. Without you, this journey would not have been ended.

And

To my country; People's Republic of Bangladesh. I am indebted to my country for building the foundation and providing me quality education.

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No words are enough to express my gratitude to my advisor, Dr. Abdel E. Bayoumi for giving me the opportunity to work under his supervision and being a part of CBM research center. I am indebted for his guidance, advice and support to pursue this degree. I would also like to thank Dr. Jamil Khan, Dr. Jeffrey H. Morehouse, and Dr. Richard Robinson for serving on my dissertation committee. I would like to extend my gratitude in particular to Dr. Robinson for his guidance and advice that helped me in completing this work.

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ABSTRACT

Condition-based maintenance (CBM) is a maintenance practice that involves regular monitoring of the mechanical condition of components of interest, processing of information collected, and then decision-making to ensure both maximizing the time interval between repairs and minimizing the number of unscheduled failures. CBM also offers early detection of failure which can prevent major breakdowns and repairs. Vibration monitoring is one of the effective techniques for condition monitoring. Health and Usage Monitoring System (HUMS) is a powerful tool for aviation industry which monitors health status and trending data. Vibration Monitoring Unit (VMU) and Modernized Signal Processing Unit (MSPU) are two forms of HUMS used in AH-64 aircraft to implement CBM enabled environment. The tangible and intangible benefits of applying CBM concepts through HUMS in Army aviation is already well established. This dissertation aims to propose methods for further evaluation of value added to the system by implementing HUMS and CBM methodologies.

This research involves two major case studies which addresses the two categories of benefits: tangible and intangible. Tangible benefits are measurable in monetary value, whereas intangibles are not. Reduction in part cost, and maintenance flight hours, increase in flight hour, decrease in mission aborts etc. are various form of tangible benefits. Intangible benefits are seen as an important indicator of overall effectiveness of CBM implementation. This creates incentives for Army personnel at all levels to adopt

this practice. This is measured from the survey responses of Army maintainers, crews and pilots. But as survey responses are subject to dynamic human behavior, this a continuous evaluation process which should be repeated time-to-time. The first case study presents a step in the direction of better understanding of how mission benefit areas like morale, sense of safety etc. are perceived by army personnel who fly and maintain Army aircraft equipped with HUMS. Response data collected from seventy-six helicopter personnel was analyzed and a multiple linear regression model is proposed reducing survey time by 30% keeping the accuracy same.

US Army is currently the world's largest user of HUMS. This system requires cost to install, monitor and maintain. It is important to measure whether the benefit outweighs the cost. The goal of the second case study is to address the possible sources of benefits, estimate costs in forms of investments, quantify them in monetary values and finally measure the effectiveness though estimating return on investment. The significance of this study lies in its data collection, interpretation and analysis process.

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LIST OF ABBREVIATIONS

AED.....	Aviation Engineering Directorate
AHB.....	After Hanger Bearing
AIC.....	Akaike's Information Criterion
AMCOM.....	Aviation and Missile Command
APU.....	Auxiliary Power Unit
CBA	Cost Benefit Analysis
CBM.....	Condition-Based Maintenance
CI.....	Condition Indicator
COM.....	Cost of Maintenance
COQ.....	Cost of Quality
DAQ.....	Data Acquisition
DCR.....	Document Control Registrar
DOD.....	Department of Defense
FEDLOG.....	Federal Logistics Data
FHB	Forward Hanger Bearing
FY.....	Fiscal Year
GA.....	Genetic Algorithm
HUMS	Health and Usage Monitoring Systems
IGB	Intermediate Gearbox
IMD.....	Integrated Mechanical Diagnostics
IVHM.....	Integrated Vehicle Health Management
KPI.....	Key Performance Indicator
MLR.....	Multiple Linear Regression
MMH.....	Maintenance Man Hours
MRSP.....	Main Rotor Swashplate
MSPU.....	Modern Signal Processing Unit

MTF.....	Maintenance Test Flight
NCS.....	NATO Codification System
NL.....	National Instrument
NIIN.....	National Item Identification Number
NLP.....	Natural Language Processing
NMCS.....	Not-Mission Capable Supply
NSN.....	National Stock Number
O&S	Operations and Support
PMCM.....	Partial Mission Capable Maintenance
ROI.....	Return on Investment
RMSE.....	Root Mean Square Error
SBC.....	Schwarz' Bayesian Information Criterion
SCARNG	South Carolina Army National Guard
SLR.....	Simple Linear Regression
TAMMS-A.....	The Army Maintenance Management System-Aviation
TGB.....	Tail Rotor Gearbox
TRDT.....	Tail Rotor Drive Train
TRSP.....	Tail Rotor Swashplate
ULLS-A	Unit Level Logistics Support - Aviation
ULLS-AE	Unit Level Logistics Support – Aviation Enhanced
USC.....	University of South Carolina
VIF.....	Variance Inflation Factor
VM.....	Vibration Monitoring
VMEP.....	Vibration Management Enhancement Program
VMU	Vibration Monitoring Unit

CHAPTER 1

INTRODUCTION

1.1 Evolution of Maintenance Management Practice

The problems faced by the world of manufacturing and service industries all the time are mostly inclined to maintaining stability between cost and profit. Other than balancing between supply and demand, keeping cost on a leash is a major issue. In most cases leaderships focus on material cost; put effort to reduce labor cost by applying effective line balancing scheme but often what is ignored is the maintenance cost. Improper maintenance practice can cost way more than can be imagined.

The condition of a mechanical component typically has an inverse relationship with time. As the time progresses, the condition starts to degrade. As time passes, the mechanical component may require one or more maintenance activities which are intended to make the components useful service life longer. If the maintenance need is not fulfilled, the component's performance may suffer, including the possibility of failure and causing significant damage of property. Figure 1.1 offers a simple diagram of the relationship between performance and time for a mechanical component. The relationship is represented by the curved line referred as the P-F curve. The P-F curve shows that as failure starts manifesting, the component deteriorates to the point at which it can possibly

be detected (P). If the failure is not detected and mitigated, it continues until a "hard" failure occurs (F).

The time range between P and F, commonly called the P-F interval, is the window of opportunity during which an inspection can possibly detect the imminent failure and address it. Preventive maintenance tasks for mechanical components are typically scheduled intervals in the elapsed time, usually hours.

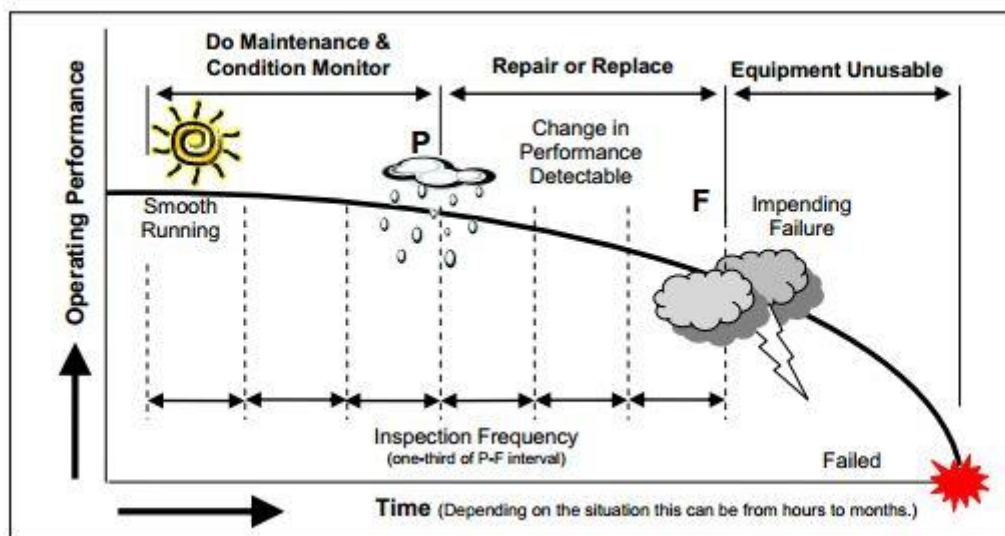


Figure 1.1: The P-F curve showing the problem identification to damage progression

A fundamental objective of mechanical component maintenance is to extend component life by reducing failure rate. Figure 1.2 illustrates hypothetical variation of instantaneous failure rate over time due to the combination of all the active failure possibilities over a mechanical component's lifetime called the "bathtub curve", it indicates that a new component has a high probability of failure because of installation problems during first few weeks of operation.

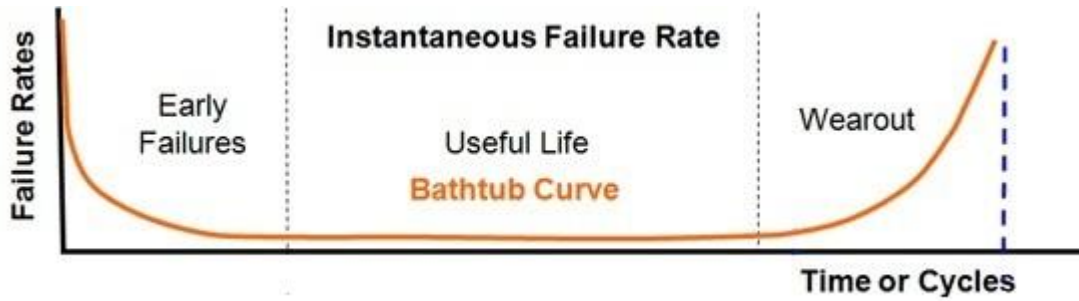


Figure 1.2: A classic bathtub curve for a mechanical component

After the initial period, this probability becomes relatively low for the useful life period. After that the probability increases sharply as time passes and the component starts to wear out. Figure 1.3 represents the cumulative failure distribution for a set of mechanical components based on the hypothetical distribution of instantaneous failure rates. The curve gives the same message as “bathtub curve” does, the failure rate increases with time and after useful lifetime, it sharply increases.

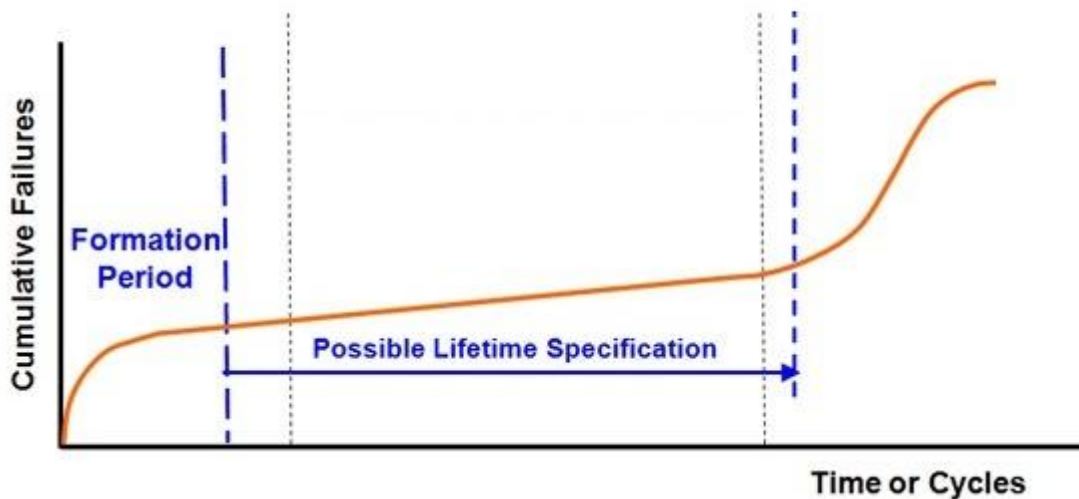


Figure 1.3: Cumulative failure distribution of a mechanical component over time

The degradation of a single component often initiates secondary damage like failure of associated components which adds cost to the original damage repair. So, the cost of repair is proportional to the stage of detection of failure of an individual component, even more so when dealing with multiple operationally independent mechanical components. Obviously then the prompt identification of potential failure should result in increased cost savings.

Cost due to improper maintenance practice is one of the major portions contributing to increase the overall cost and thus to reduce profit margin. Maintenance cost does not involve only the cost of parts of machinery, but also the cost of lost effective operating hours, maintenance actions, materials and parts purchase, even loss of business. These are all the cases where we can put monetary value. But there are also some cases where it's hard to put a monetary value but the effect cannot be ignored. Such fields are the intangibles. We cannot put a monetary value on the confidence, morale, sense of time savings or sense of safety of an operator. But decreasing any of these factors can result into a loss of money. That's the reason behind adopting an appropriate maintenance scheme.

The initial maintenance practice is to wait for maintenance until the system breaks down. This is the reactive maintenance approach, also known as break-down maintenance. In this practice, people keep operating the machinery until it fails and becomes unable to perform. This kind of practice leads to the interruption of the production process without any prior notice. The process remains inactive until the fault has been found and fixed. During that fixing process, that particular machine or system

loses its functional hours. Also, as this kind of practice waits until the machine broke; it reduces the functional life of that machine.

To get rid of this kind of unwanted shutdown, preventive maintenance is introduced. The main concept for preventive maintenance is to avoid unwanted break down by doing maintenance at a regular interval; which can be time-based or usage-based. At time-based preventive maintenance, maintenance is done after a certain period of time which can be hours, days, weeks, months or so. The usage-based maintenance suggests performing maintenance upon usage. Oil change in automobile is a perfect example to understand this concept. Changing the engine oil of car in every 6 months or 5000 miles, whichever comes first, is a common case for preventive maintenance. But preventive maintenance may result into changing machine parts even if they have functional life left. Or the component, that seems to be perfectly functional during one scheduled maintenance, may get worse before reaching to another scheduled one.

To make the maintenance practice more cost effective, why not perform the action only when needed, preventing the failure even before happening? Only by closely monitoring the health of machinery component of interest can lead to such event. Condition-based maintenance (CBM) represents such maintenance concept. During this practice, the health of the component is continuously monitored using sensors and the parameters that represent the health status are collected, analyzed and actions are taken based on those facts. The common parameters are vibration, temperature, acoustic emissions, torque, power usage etc.

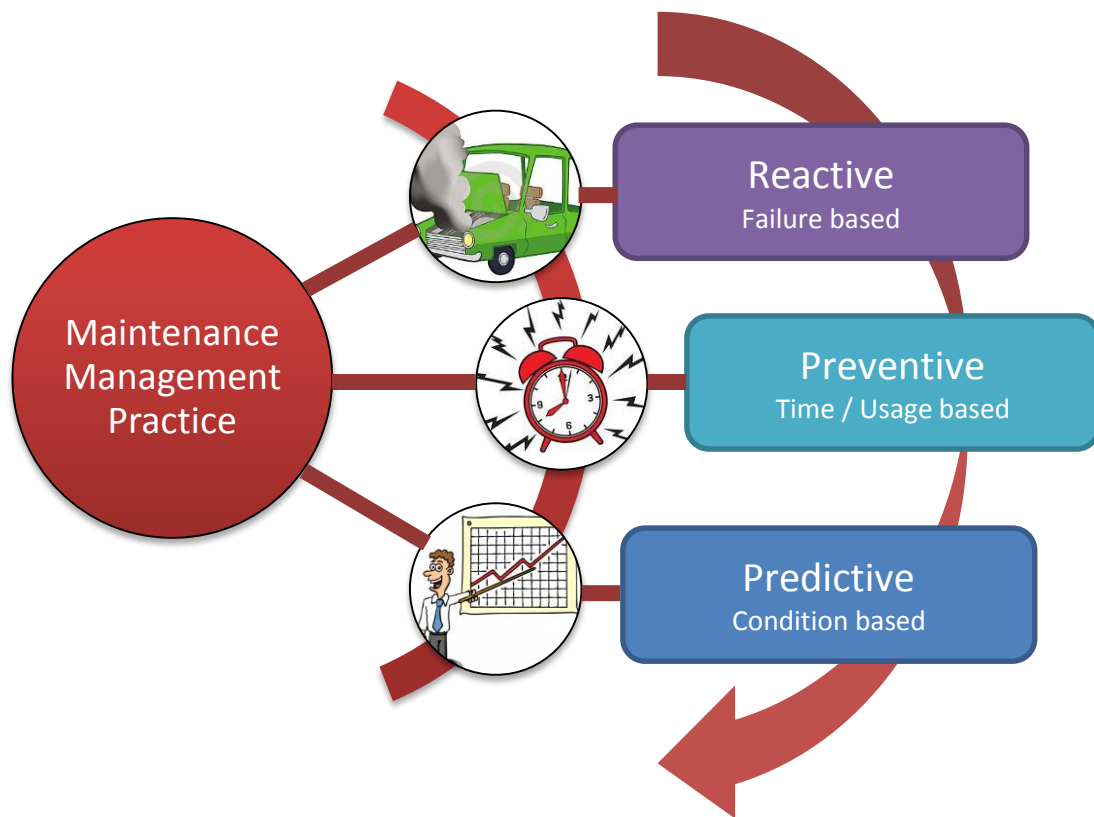


Figure 1.4: Evolution of maintenance management practice

1.2 Condition Monitoring

Condition-based maintenance is a goal-driven process for better maintenance of existing systems. CBM uses the data from the actual operating condition of the system components to optimize system operation by maximizing the interval between repairs and minimizing the number and costs of unscheduled repairs and downtime. This allows the transformation from reactive maintenance procedures to proactive ones. There are several techniques available for condition monitoring among them vibration monitoring, oil analysis, thermography and acoustic emission are notable.

Displacement, velocity and acceleration are the key characteristics of vibration measurement of any rotating machinery. The condition of a machine can be diagnosed from the measurement of vibration amplitude. If one or more parts in a machine are

unbalanced, misaligned, loose, eccentric, out of tolerance dimensionality, damaged or reacting to external forces, the anomalies can be detected from the deviation of their vibration signature.

If faults are not directly related to acceleration, vibration monitoring will not be much effective for condition monitoring. In such case other techniques like thermography, oil analysis, ultrasonic test proves to be helpful.

Embracing a CBM program for a system or component includes installing additional hardware (like sensors, accelerometers, thermocouples), using software (for data collection, analysis), training personnel, using computational and decision making technique (data mining, data fusion) etc. It is an involved, comprehensive process that can require additional costs compared to more traditional maintenance process. It is important to know how much value is added through the implementation.

1.3 CBM Practice in US Army

The US Army has been engaged in numerous programs focusing CBM implementation on rotary aircraft. These programs have achieved great success over years in fault detection and health diagnostic and prognostic (Batzel, T.D. et al., 2009, Grabil, P. et al., 2002). As a continuation of such initiative South Carolina Army National Guard (SCARNG) with collaboration of US Army has been practicing CBM methodologies and deploying Modernized Signal Processing Unit (MSPU). With the aid of MSPU the critical and failure prone components of aircraft such as engines, gearboxes, drive train, rotor etc. are continuously monitored. Mechanical defects like drive shaft bending, bearing fault, grease leak etc. are detected using the sensor data and analysis

techniques like signal processing (Keller et al., 2005, Samuel and Pines 2008, Dempsey et al., 2008), wavelet techniques (Samuel et al., 2009) etc. Currently MSPU is deployed on Apache, Chinook and Blackhawk aircraft. Such faults are detected

1.4 CBM Practice at the University of South Carolina

University of South Carolina (USC) has been working very closely with SCARNG, Aviation and Missile Command (AMCOM) and Aviation Engineering Directorate (AED) to promote and expand the concept of CBM methodologies and practice among Army rotorcraft. USC's research initiatives include, but not limited to component testing for deep understating of faults occurred during operation, sensor data collection and integration to estimate damage progression, to develop model to calculate remaining useful life, quantification of added value from CBM practice etc. The full scale AH-64 tail rotor drive train (TRDT), main rotor swashplate (MRSP), experimental drive train and auxiliary power unit (APU) test stand made the CBM research center at USC an ideal place for cutting edge research and innovation. The TRDT test stand consist of forward hanger bearing (FHB), after hanger bearing (AHB), intermediate gearbox (IGB), tail rotor gearbox (TGB) and tail rotor swashplate (TRSP). These components are driven by a computer controlled 800 HP motor. The motor can achieve 150% of normal operating speed of an aircraft. The torque is generated by a similar motor which can place a load of 1200 fl-lbs on the system. This puts back 70% of the generating energy to the original motor. Vibration and temperature data are collected from several locations on TRDT test stand. MSPU generates condition indicators (Cis) where national instrument

(NI) data acquisition (DAQ) system collects raw vibration data. Temperature data is collected from thermocouples. Figure 1.5 shows a detailed image of TRDT test stand.

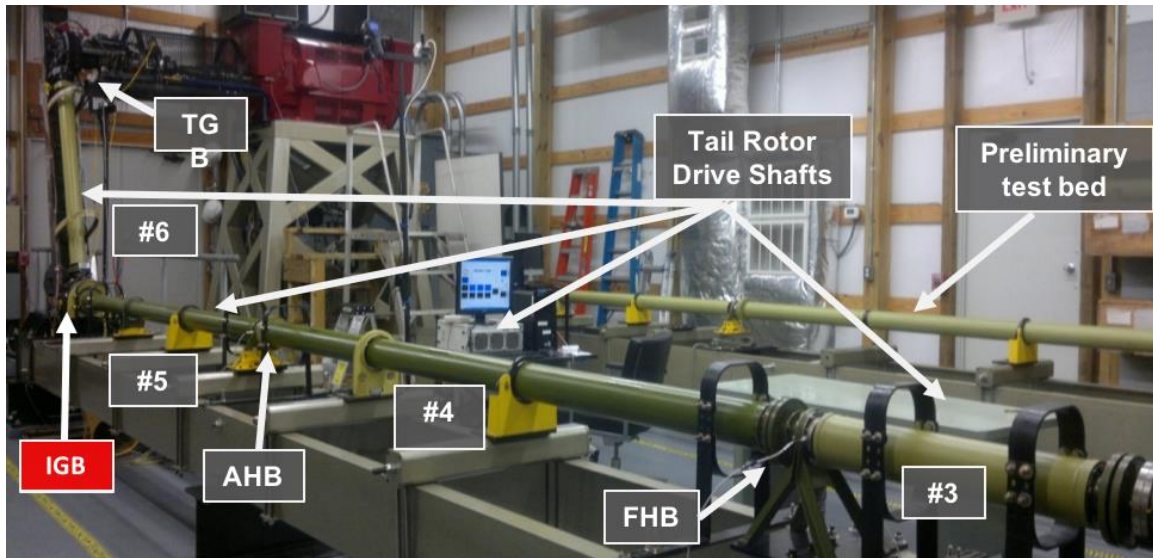


Figure 1.5: TRDT test stand at the CBM research center at USC

1.5 Motivation

CBM is a proactive maintenance practice, which collects information of critical components using sensors: it analyzes, understands and recommends action as needed. SCARNG has been engaged in practicing CBM since 1998 through VMEP. Implementation of HUMS in Army aircrafts is one of the key factors that helps the practice move from traditional to predictive maintenance. Benefits achieved from HUMS deployment on aircrafts can be split into two categories; basic and mission. Basic benefits are tangible and are quantifiable by means of reduced flight hour cost, operating cost, HUMS investment cost, test flight cost etc. Mission benefits are the soft benefit areas which consist of operational readiness, morale, performance, sense of safety and sense of time savings. As CBM practice requires some initial amount of investment, it is

important to know whether the benefits outweigh the costs to justify the economic effectiveness.

It has been seen that many predictive maintenance program failed to generate measurable benefits after implementation. These failures were not related to technical limitations rather they were unable to make the necessary changes in the work place to adopt new practices which would allow maximum utilization of predictive tools that have been introduced. Personnel often do not understand the sheer need for a change to better, more effective practice and are reluctant to voluntarily welcome new technology. To resolve this issue, a group of people from the current workforce are trained to ensure maximum return on investment as further adaptation depends upon their performance. For this reason, it is necessary to understand the attitude of flight and maintenance crews towards different aspects of mission benefits like performance, morale, and operational readiness, sense of safety and sense of time savings. This information can be attained through measuring attitudes. A common way to assess person's attitude towards something is to take a survey.

Bayoumi et. al performed an annual cost savings analysis of the VMEP for AH-64 and UH-60 aircraft fleets. The major findings of this study was presented in forms of savings in part cost, operational support, increase in mission capability rates, decrease in maintenance and increase in total flight time. The study also investigates the intangible benefits which include an increase in confidence for early diagnosis, an increase in attention and performance, an increase in personnel morale and increase in safety and sense of safety. With the continuation of previous study, Bayoumi et. al also explored a larger timeframe to investigate the cost savings in a later study. The 8-year period of

VMEP which shows a \$1.4 million savings in parts costs and \$2.1 million in parts and operational support cost. Later, Blechertas et. al performed another cost analysis for only AH-64 aircrafts and presented the cost savings between two alternatives, baseline and VMEP. The results of this study indicates the improved ability of maintenance crews to adopt VMEP system by decrease in maintenance test flight hours at SCARNG. Also, a decrease in unscheduled maintenance action and replacement parts costs are an indication of effective maintenance practice compared to traditional.

Cost-benefit analysis has always been a prime requirement to demonstrate the success of CBM practice. This research work aims to propose a framework to calculate ROI and use army aviation historical data to validate the model and also evaluate the economic effectiveness of CBM implementation in SCARNG.

1.6 Organization of Dissertation

The remaining of this dissertation is organized as follows. In chapter 2, the concept of HUMS, its structure and uses, the background of VMEP project and the concept of basic and mission benefits are introduced to the reader. This will facilitate the understanding for the following chapters that encompasses the analysis of basic and mission benefits and the development of the tool to estimate the added value to the system due to HUMS implementation and CBM practice.

In chapter 3, a comprehensive statistical analysis is performed on the outcomes of Likert scale based survey which is accomplished earlier. Different analysis techniques are utilized here which includes multiple linear regression (MLR), hypothesis testing, collinearity test and most influential mission benefit indicator determination used model

selection criteria. Then a MLR model is proposed which will predict one the mission benefit indicator; performance based on the remaining mission benefit indicator.

In chapter 4, maintenance log and flight records are presented as a reliable source to estimate the value added to the system. This chapter discusses the type of attributes and method of information extraction from maintenance logs and flight records, the method of cost calculation using those attributes and finally estimation of economic effectiveness using return on investment (ROI) method.

Summary, conclusion and commendations of the dissertation are presented in chapter 5.

CHAPTER 2

BACKGROUND

2.1 Health and Usage Monitoring System (HUMS)

Health and Usage Monitoring System (HUMS) is a sensor-based diagnostic system which has a broad range of application starting from the offshore oil and gas industry to business jets, drones, fixed wings aircrafts, military aircrafts etc. Since the emergence of HUMS in early 1990s, the system has been matured in recent years. Over the past twenty years, the US army has been actively installing and utilizing onboard HUMS for its fleet of Apache, Blackhawk, Chinook, Kiowa helicopters.

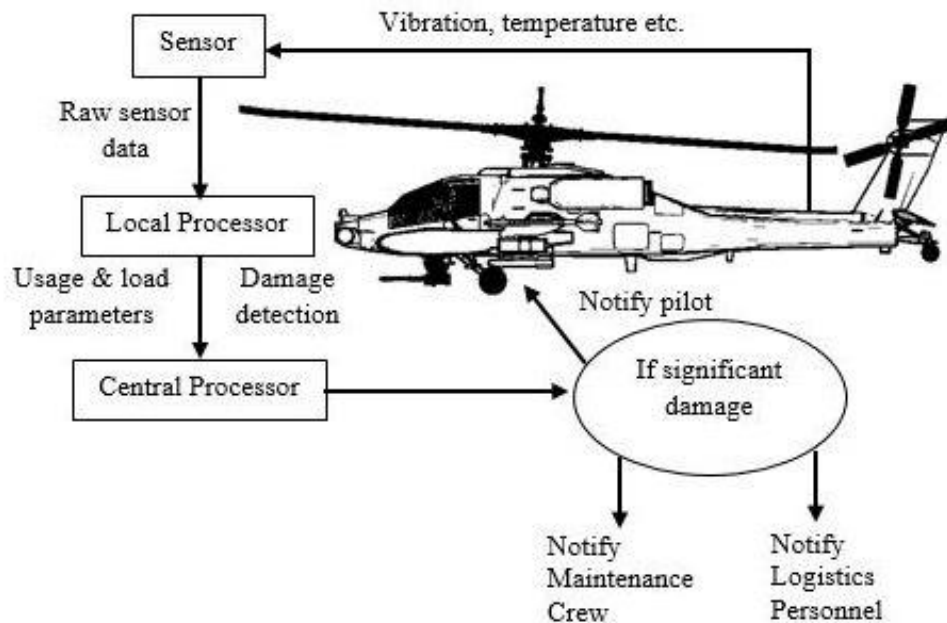


Figure 2.1: Schematic diagram of a HUMS architecture for structural application.

Typically, HUMS installed on an aircraft consists of some certain sub-elements:

- A set of on-board sensors and their connecting systems.
- On-board data acquisition and processing unit
- On-board recording system
- On-board display system, and
- A ground segment to download the sensor data for further analysis.

Sensors commonly used but not limited to in HUMS are:

- Acoustic emission: for damage, cracks, delamination, and impact detection.
- Strain gauge: for strain measurement for fatigue-prone parts.
- Thermocouple: for temperature measurement in bearing, gearbox, lubricating oil, etc.
- Pressure transducer
- Vibration sensor or accelerometer, etc.



Figure 2.2: A MSPU unit with exposed top

The primary concern of HUMS is to enable aircraft to monitor the health of rotary components of a mechanical system and perform condition monitoring of critical components in the drive train. HUMS continuously records structural and transmission usage, transmission vibrations, rotor track and balance information, and engine power assurance data. Besides usage and event analysis, it also records parametric data from the aircraft's bus. HUMS collects speed, torque, pressure and temperature data as well as vibration, rotor track and balance data from a number of sensors instrumented on critical areas of the structure. Sensors are linked to processors using pre-defined algorithms that perform health assessment and evaluate the criticality for a particular component. This information is displayed to the pilot and also is saved for future use by maintenance and logistic personnel.

2.2 HUMS in AH-64 Aircraft

AH-64A and D aircraft at South Carolina Army National Guard (SCARNG) from which The Army Maintenance Management System-Aviation (TAMMS-A) data has been collected are equipped with a Modernized Signal Processing Unit (MSPU), which is a form of HUMS commercially supplied by Honeywell. The AH-64 installment of this HUMS device implements 18 accelerometers and 3 tachometers for vibration and usage sensing. (Adams, D. et al., 2009). The accelerometers are located throughout the aircraft, particularly where vibration is a known problem for the AH-64, such as tail rotor drive train (TRDT) components.



Figure 2.3: Boeing AH-64D Apache

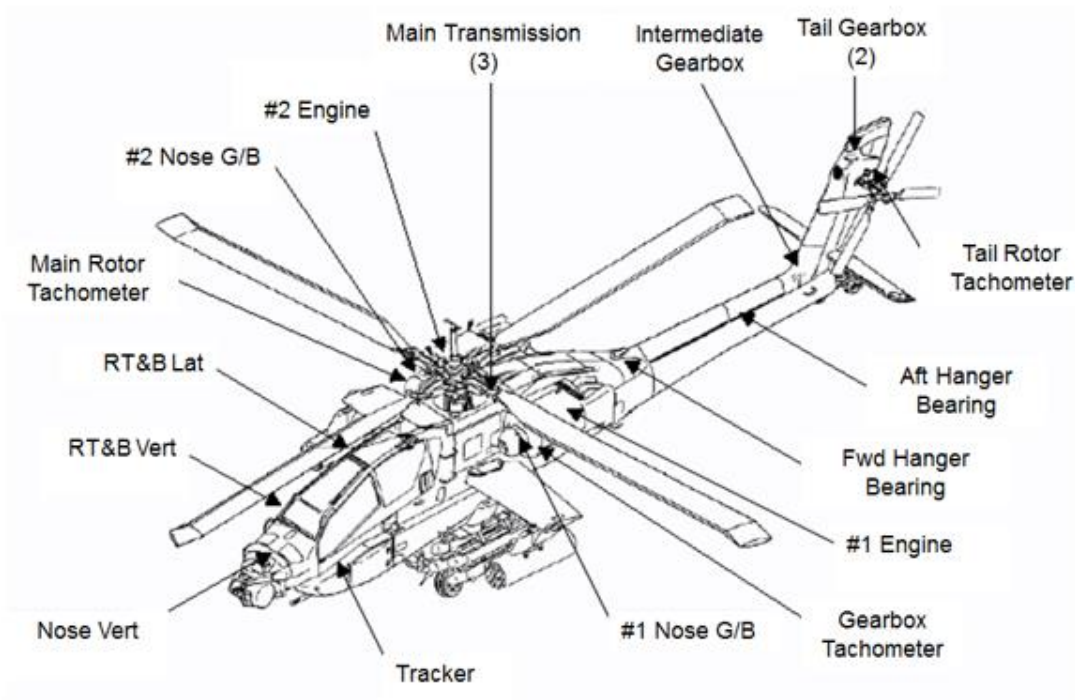


Figure 2.4: The on-board sensor locations for AH-64D aircraft

2.3 VMEP Project

Vibration Management Enhancement Program (VMEP) is a government-industry-academia joint initiative; aimed to evaluate the cost and effectiveness of on-board vibration monitoring (VM) system (P. Shanthakumaran et al., 2010). This system was developed by SCARNG with the contributions from US Army and University of South Carolina (USC) and then was installed on AH-64 and UH-60 aircraft. The goal of VMEP project is to provide an annual cost saving analysis of the program and correlate the vibration signal with ULLS-A database to create a Cost Benefit Analysis (CBA) model. The model uses ULLS-A data as input and estimates cost savings in forms of parts cost, operational support, mission capability rates, reduction in unscheduled maintenance and increase in total flight hour. The model uses test flight hours, hours per flight, cost per flight hour, VMEP investment cost, number of VM system installed aircraft etc. as input variable while annual cost saving analysis (Abdel Bayoumi et al., 2005). As of February 2009, the program had \$33.4 million saving in part costs and \$38.3 million savings in parts and operation support (Blechertas, V and Bayoumi, A. et al., 2009). Besides tangible benefits, the model also addresses intangible benefits such as morale, performance, sense of safety, sense of time savings etc. through a Likert-scale survey. Army personnel from various establishments participated in the survey and their responses indicate VMEP results into the improved safety, sense of safety, morale, performance etc. and increases overall confidence.

2.4 Basic and Mission Benefits

Benefits achieved from HUMS deployment on aircrafts can be split into two categories; basic and mission. These are important in measuring economic effectiveness of CBM using a cost-benefit model. Basic benefits are tangible and are quantifiable in terms of monetary value. The basic benefits identified and thus calculated from flight records, maintenance records, and logistics records are reduced flight hour cost, operating cost, HUMS investment cost, test flight cost etc.

Mission benefits are the soft benefit areas which cannot be measured directly in monetary values, but are very important element in cost benefit analysis of HUMS implementation. These mission benefits consist of operational readiness, morale, performance, sense of safety and sense of time savings. This information can be attained through measuring perception of HUMS users. A Likert-scale based survey is designed from a day-long brainstorming session between USC and SCARNG personnel. The survey could be five-scale or seven-scale. The survey questions are intended to capture the behavioral traits of maintainers, crews and pilots.

CHAPTER 3

STATISTICAL ANALYSIS OF HUMS USERS' PERSPECTIVE TOWARDS MISSION BENEFITS USING MULTIPLE LINEAR REGRESSION

3.1 Introduction

A Health and Usage Monitoring Systems (HUMS) is a sensor-based real-time diagnostic system which collects data from numerous critical points of mechanical structure such as engines, rotors, gearboxes and drive shafts and processes the data using a predefined algorithm. The results provide information to flight and maintenance crews. Based on the provided information, decisions are taken for performing maintenance actions. HUMS is closely related to the implementation of CBM and plays an important role to the adoption of CBM instead of preventive and/or reactive maintenance. The aim of this case study is to analyze how the flight and maintenance crews accept this new concept of maintenance and to understand how their attitude towards performance gets influenced by other attitude factors. HUMS refers to any onboard vibration monitoring system including Vibration Monitoring Unit (VMU), Vibration Measurement Enhancement Program (VMEP), Modernized Signal Processing Unit (MSPU), Integrated Mechanical Diagnostics - Health and Usage Management System (IMD-HUMS), Integrated Vehicle Health Management - Health and Usage Management System (IVHM-

HUMS), etc. Implementation of HUMS is one of the key factors that helps the practice move from traditional to predictive maintenance

It has been seen that many predictive maintenance program failed to generate measurable benefits after implementation. These failures were not related to technical limitations but rather they were unable to make the necessary changes in the work place to adopt new practices which would allow maximum utilization of predictive tools that have been introduced (Mobley, 2002). Personnel often do not understand the sheer need for a change to better, more effective practice and are reluctant to voluntarily welcome new technology. To resolve this issue, a group of people from the current workforce are trained to ensure maximum return on investment as further adaptation depends upon their performance. For this reason, it is necessary to understand the attitude of flight and maintenance crews towards different aspects of mission benefits like performance, morale, operational readiness, sense of safety and sense of time savings. Studies have been carried out measuring HUMS effectiveness in deployment both in rotorcraft and land vehicles (Land, J.E., 2001, Ludovici, D. et al., 2013). These studies are mostly focused into design and capability assessment, measuring economic feasibility of implementation (Hess, R. et al., 2001). Fraser recommended in favor of using HUMS in military helicopter fleets as adopting this technology would be economically beneficial for over 75% rotorcraft of the fleets (Fraser, K.F., 1996). Bayoumi et al. analyzed surveyed responses of personnel from different establishment. The chief finding was to highlight intangible benefits such availability, morale, safety, mission aborts etc. and their improvements (Bayoumi, A. et al., 2005). In this research study, efforts are taken to

address the relation among mission benefit areas, so that for future adaption of HUMS, leadership may take decisions more easily on a user survey with a fewer question.

3.2 Perspective Measurement and Likert Scale

An attitude can be described as a person's evaluation and feeling towards some object or event, which in turn may affect a person's behavior. Human response is a dynamic process, guided by certain cognitive and behavioral rules, and influenced by physical and psychological factors like memory, knowledge, emotions etc. According to social psychologist attitude is comprised of three major components; cognitive, affective and behavioral (James, S. N., 2009). Knowledge or belief of a person is represented by the cognitive component. The feeling that is produced by the object or event is the affective component of attitude. The behavioral component is a pre-disposition to act toward the object in a particular way. Besides these three components, attitude has two important aspects. One is direction which can be positive or negative and another is intensity that represents strength of feelings, which can be strong or weak. Among many methods, a Likert scale is an attitude scale, which can be tested for reliability assessment of the individual or collective item. This reliability assessment might use the correlation between individual or aggregated items score (Likert, R. A., 1932). The Likert scale is the mostly used method for attitude measurement as it is easy to understand and respond to. Dr. Rensis Likert, a sociologist at the University of Michigan, developed this technique back in 1932 as a means of measuring psychological attitude in a scientific way. Originally five response choices were proposed ranging from strongly disapprove to strongly approve. The number of response options in scales usually vary from five to

seven. The scale uses agree-disagree format which contains information on both direction and intensity. Studies show that five or seven point scales are advantageous for obtaining responses to survey questions. Since they allow for the discrimination of both the direction and intensity; and they permit a neutral or middle response (Alwin, D. F. and Jon, A. K., 1991). The individual or aggregated responses are used to establish correlation between quantitative variables. This research attempt also takes initiative to explore any relationship present between performance attitude and remaining variables and if present, to express that relation using multiple linear regression analysis techniques and to cross validate that relation.

3.3 Regression Analysis

The regression model is a statistical technique to explore the quantitative relationship between an explanatory variable and response variable (R. Lyman Ott, 2010). An explanatory variable is also termed as independent variable and its probability distribution are ideally known in advance by the experimenter or measured with negligible error. On the other hand, response variable is known as dependent variable and its probability distribution changes with the value of explanatory variable. From the functional relation between these two types of variables, the user can explore the effect of explanatory variable on response variable. In most of the cases, a linear function is assumed. If the linear function does not fit the data properly, non-linear functions might be used. In a simple linear regression (SLR) model, response variable is expressed as a linear function of a constant, coefficient, independent variable and random error;

$$y = \beta_0 + \beta_1x + \epsilon \dots \dots (3.1)$$

where, y = response variable,

β_0 = intercept,

β_1 = constant slope,

x = explanatory variable, and

ϵ = random error.

Regression analysis aims to find the best fitted straight line for prediction. For that reason, the intercept and slope are calculated in such a way which will minimize the total squared prediction error. The random error captures the effects of all the factors that might affect the dependent variable. As the values of independent variable is predetermined, ϵ is the only source of randomness. ϵ is the random error modeled as:

- The expected value of errors are zero, that is, mean is zero.
- The errors have same variance
- They are independent of each other, and
- They are normally distributed

Regression model can be used for prediction also, if unit of association is present between explanatory and response variable. In simple linear regression, the model contains only one independent variable and using the linear relationship, dependent variable can be predicted. In general, the prediction equation can be written as

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x \dots \dots (3.2)$$

where, \hat{y} = response variable to be predicted,

$\hat{\beta}_0$ = intercept of the fitted regression function, and

$\hat{\beta}_1$ = slope of the fitted regression function,

In multiple regression model, response variable is related to a set of explanatory variables. The assumptions for SLR model are also valid for multiple linear regression (MLR) model. Unlike SLR, correlation is also important not only between the independent variable and the dependent variables, but also between independent variables. The predictive effect of independent variable is clearly visible in SLR, but this is quite complex for MLR. Due to the presence of collinearity between independent variable the regression coefficients will be not be constant and will changed as variables are added or deleted. To measure the effect of collinearity, the variance inflation factor (VIF) is a useful tool. The higher the value of VIF, the more the effect of collinearity between independent variables is present. VIF is calculated using the following expression:

$$VIF = \frac{1}{1 - R_j^2} \dots \dots (3.3)$$

where, R_j^2 is the R^2 value for x_j variable only, making rest of the variables independent. If VIF is zero, no collinearity is present in that case. If VIF value is ten or more, acute collinearity is present between independent variables. In such case, the predictive power of independent variable will be hard to estimate.

3.4 Concept

Condition-based maintenance is an information based maintenance technique which is applicable on any mechanical system and components. By using the data from actual operating condition of the system components, CBM optimizes system operation by maximizing the interval between repairs and minimizing the number and costs of unscheduled repairs and downtime. Since 1998 the University of South Carolina (USC)

and the South Carolina Army National Guard (SCARNG) have engaged in a number of research programs focusing on CBM for US Army Aviation equipment, especially Army Rotorcraft. Those researches were aimed at reducing Army Aviation maintenance costs, reducing the maintenance burdens on soldiers and improving equipment availability. USC's previous efforts focused on the measurement of maintenance test flights (MTFs), part costs and the percentage of unscheduled maintenance occurrences as well as identification of various intangible benefits like safety, performance, morale, operational readiness etc. (Bayoumi, A., et al., 2005, Vytutas, B. et al., 2009).

3.5 Assumption

A few assumptions were made for the experiment conducted:

1. Individuals who participated in the survey have both ability and motivation to report attitudes.
2. Observations are assumed to be independent.
3. Variables i.e. operational readiness, morale, performance, sense of safety and sense of time savings; have a normal distribution.
4. The difference between any two consecutive alternatives are assumed to be same and uniform. For example, the difference between "Strongly Agree" and "Agree" is same as that of between "Agree" and "Neutral".

3.6 Method

USC's research team, crew chiefs and pilots created a set of questions designed to address aspects of mission benefits areas; operational readiness, morale, performance,

sense of safety and sense of time savings as they are related to operating and maintaining Blackhawk, Apache etc. helicopters. Finally, a Likert scale based questionnaire was created to use in surveying various units in the National Guard and Regular Army who had experience in using HUMS. Over the time spanning March 2010 to April 2011, seventy-six helicopter personnel took this survey. The survey questionnaire has twenty-five questions and participants responded to them using six alternatives; Strongly Agree (5), Agree (4), Neutral (3), Disagree (2), Strongly Disagree (1) and I Don't Know (0).

Twenty-five survey questions were categorized into five groups based on the benefits area they were focused on; which are operational readiness, morale, performance, sense of safety and sense of time savings. Eight of twenty-five questions of the survey were focused on performance, four were on operational readiness, six belong to morale, three to sense of safety and four to sense of time savings. Table 1 shows some of the grouped questions with corresponding benefit areas.

Table 3.1. Sample question from the survey questionnaire

Benefit area	Corresponding survey questions
Sense of performance	<ul style="list-style-type: none"> • HUMS enhances our ability to reliably detect impending component failure and problems • HUMS enhances the troubleshooting process
Operational readiness	<ul style="list-style-type: none"> • HUMS results in less frequent mission aborts due to maintenance • HUMs improve operational stability
Morale	<ul style="list-style-type: none"> • HUMS improves the overall maintenance decision making process • Having HUMS on the aircraft increases my confidence
Sense of safety	<ul style="list-style-type: none"> • There is a greater margin of safety with HUMS on the aircraft

Sense of time saving	<ul style="list-style-type: none"> • HUMS reduces the lead time for obtaining components that need service • HUMS reduces component change frequency
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In this research approach, average of response scores from flight and maintenance crews are aggregated based on the focus area. Correlation was checked first by plotting a scatter diagram and then influence of other particular mission benefits on users' performance is investigated. In this research work, it is assumed that the functional relationship between variables is linear. During the analysis, 80% of the sample data was used as training set for model building and 20% as the testing set. Before proposing a MLR model, regression assumptions were checked using scatter plot, residual vs predicted plot, residual vs time plot and normal plot. The scatter plot provides an initial check of the linearity assumptions for regression. In the scatter plots, each explanatory variable was paired with the response variable, performance and the presence of linearly increasing or decreasing trend with 4 constant noise was looked for. For example, the average response for performance was plotted against that of morale, where each data point represents response from each survey participant. As eight of twenty-five questions of the survey were focused on performance, the aggregated score for performance ranges from 0 to 40, and average ranges from 0 to 5. Similarly aggregated score for six morale based response ranges from 0 to 30, and average ranges from 0 to 5.

By careful observation of residuals plots, the assumptions can be assessed in more detail. Commonly, the residuals are plotted against the predicted value estimated using the fitted regression function. Evenly scattered residuals around the zero line along the range of predicted values indicate the linear relationship with constant variability of

residuals with predicted values. The residual vs time plot represents the distribution of residuals with the number of observation in sample used for regression. Any presence of pattern, violates the assumption that the model was correctly specified. Normal Q-Q plot of residuals is the plot of residuals against the values they would be expected to take if they come from a standard normal distribution.

After checking assumptions, a valid multiple linear regression (MLR) model was proposed to relate the attitude towards performance to a set of 4 variables; attitude towards operational readiness, morale, sense of safety and sense of time savings. Here, performance was considered as the response variable and the remaining four were explanatory variables. The aim of proposing a model was to observe the individual influence of variables on performance and also to arrive at a conserving sub-model of variables that still well explains performance. Test data was then plugged into the obtained regression model and the model accuracy was measured.

3.7 Model Selection Criteria

Multiple linear regression (MLR) relates a number of explanatory variables with a response variable. When collinearity is present among the explanatory variables, it is hard to understand their individual influence on response variable. To avoid collinearity, explanatory variables are needed to be chosen with care based on a number of criteria such as:

1. Coefficient of determination: This is the squared value of correlation coefficient, r .

For SLR coefficient of determination is expressed as r^2 and for MLR is R^2 .

Correlation coefficient measures the strength of linear relationship between two variables. R^2 value ranges from 0 to 1 and model was chosen with high R^2 value.

$$R^2 = (SS_{Total} - SS_{Residual}) / SS_{Total} \dots \dots (3.2)$$

2. Root mean square error,

$$RMSE = \sqrt{SS_{Residual} / n - (k + 1)} \dots \dots (3.3)$$

Model was chosen with minimum RMSE.

3. Mallows' C_p ,

$$C_p = SS_{Residual_p} / ME_{Residual_p} - (n - 2p) \dots \dots (3.4)$$

Model was chosen for the smallest p such that $C_p \approx p$.

4. Akaike's information criterion,

$$AIC = n \times \log(SS_{Residual} / n) + 2p \dots \dots (3.5)$$

Model with smallest AIC was chosen where AIC can be negative.

5. Schwarz' Bayesian Information criterion,

$$SBC = n \times \log(SS_{Residual} / n) + p \times \log(n) \dots \dots (3.6)$$

Model with smallest SBC was chosen where SBC can be negative.

3.8 Analysis

The assumptions for multiple linear regression were checked first from scatter plot. From figure 3.1 to 3.4, four scatter plots are presented where positive linear increasing pattern with constant noise was observed. This indicates a positive linear correlation between the variables supporting the first assumption of regression. For

example, the average response for performance was plotted against that of morale, where each data point represents average score of responses from each survey participant (figure 3.1).

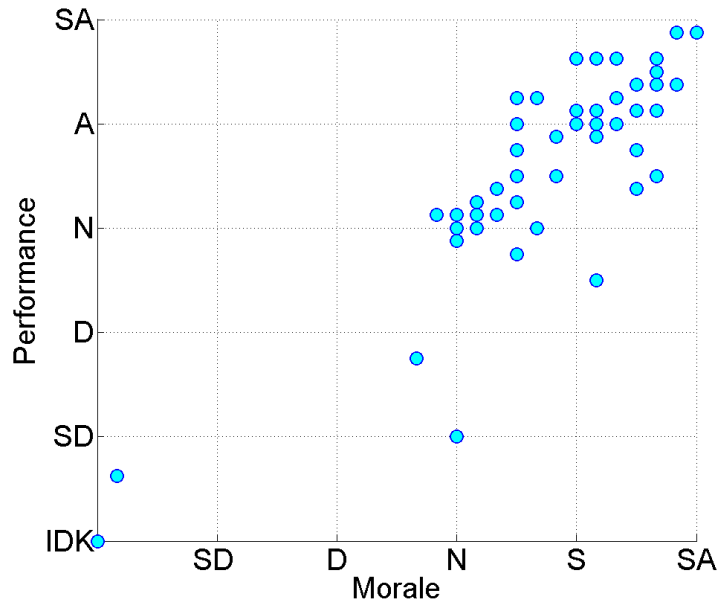


Figure 3.1: Scatter plot of average response for performance against that of morale

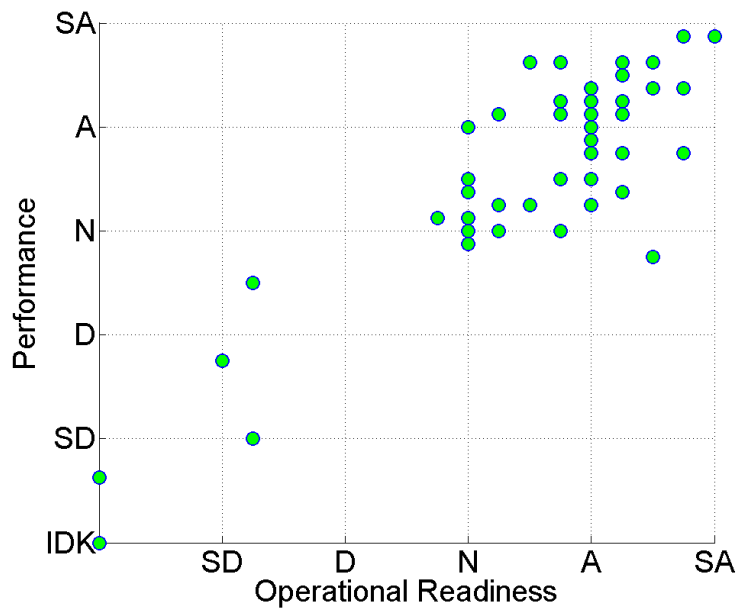


Figure 3.2: Scatter plot of average response for performance against that of operational readiness

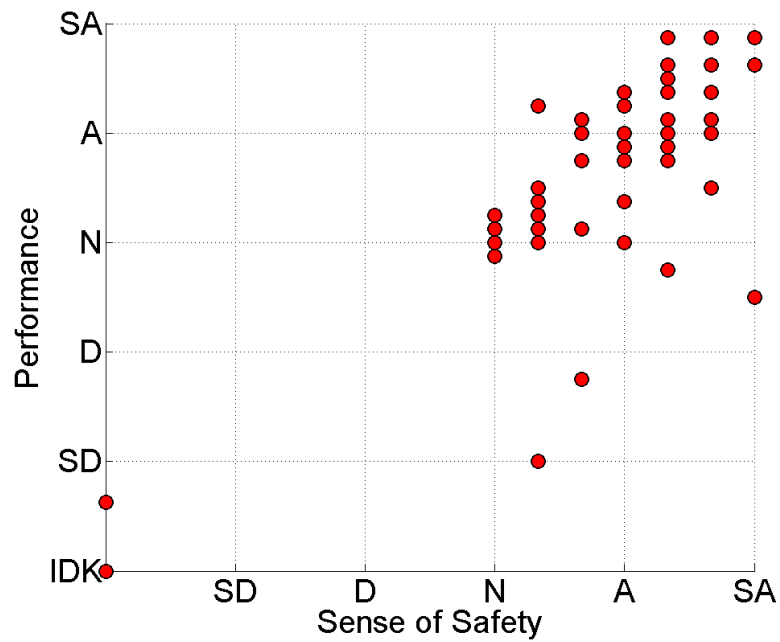


Figure 3.3: Scatter plot of average response for performance against that of sense of safety

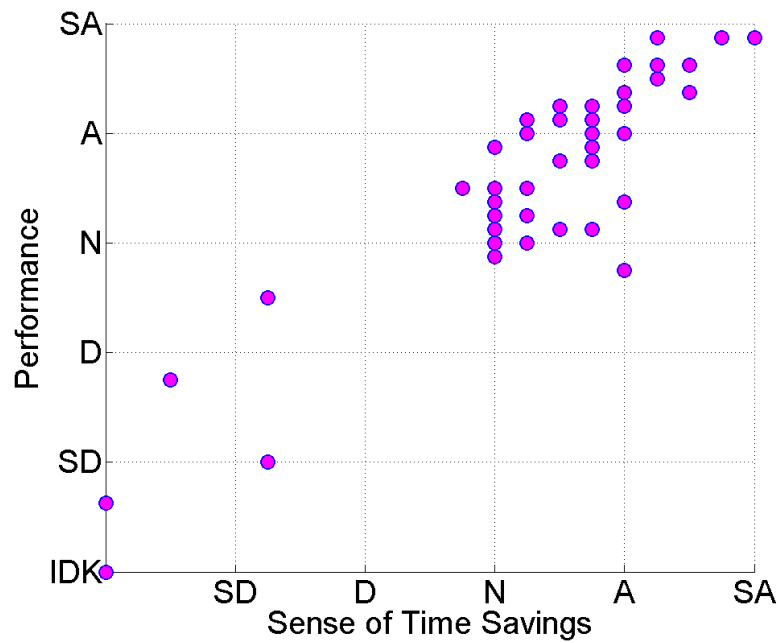


Figure 3.4: Scatter plot of average response for performance against that of sense of time savings

The next step is to investigate the assumptions made to support multiple linear regression model. Here residuals are first plotted against predicted value and then, against the number of observation to have a close look at the assumptions. From figure 3.5 it is visible that the residuals are mostly scattered around the zero line if extreme values are overlooked. In the residuals plot against the number of observation in figure 3.6, no pattern was visible which supports the assumption of uncorrelated error with number of observation. The assumption of normality of residuals seems appropriate from the nearly linear Normal Q-Q plot in figure 3.7. However, in the Shapiro-Wilk normality test p-value ($8.518e-5$) is less than 0.01, which rejects the null hypothesis of normality.

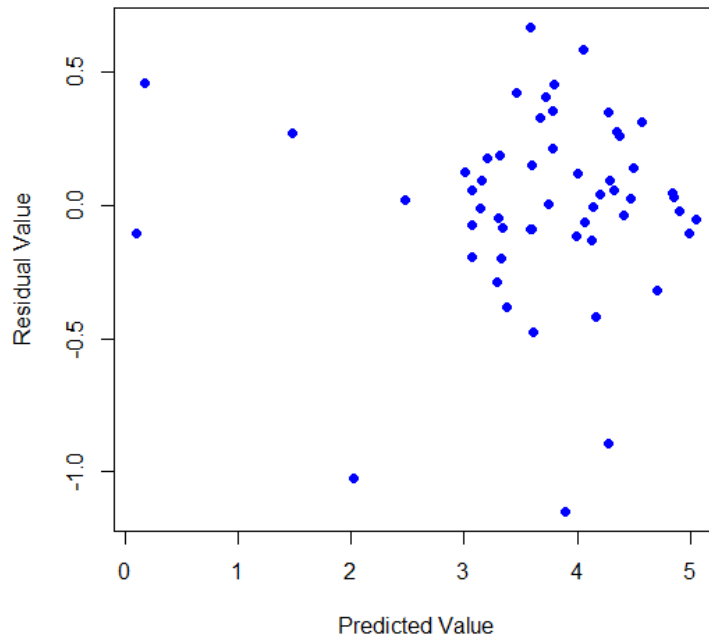


Figure 3.5: The calculated residual of the MLR model is scattered randomly around the mean.

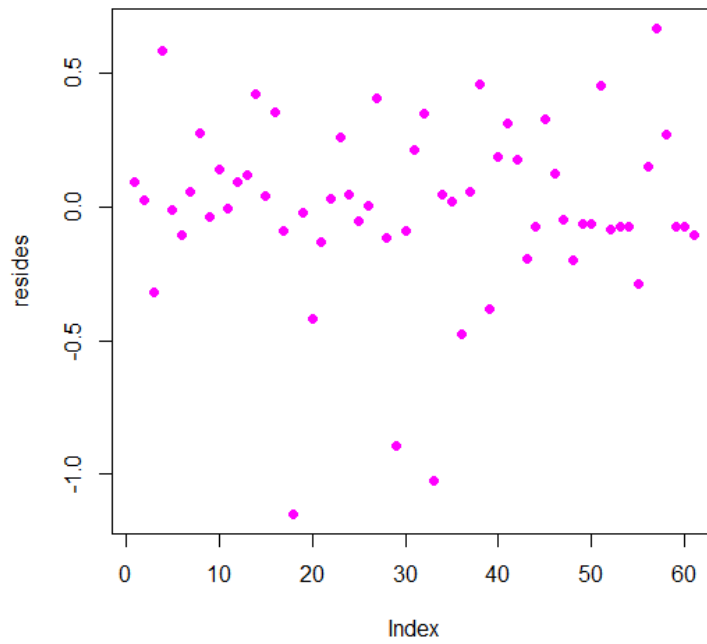


Figure 3.6: The absence of any pattern in residuals with number of observation

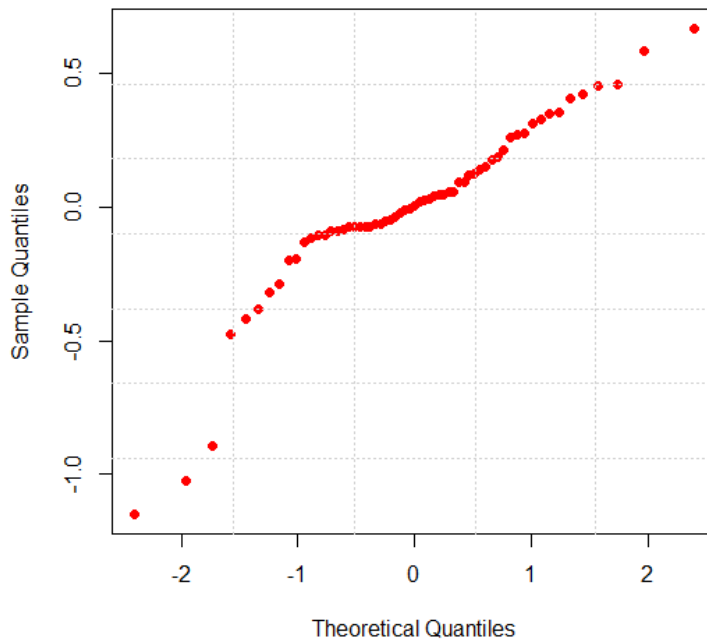


Figure 3.7: Normal Q-Q plot for normality test

The fitted regression line is:

Performance

$$= 0.10632 + 0.39024 \times \text{Morale} + 0.05977 \\ \times \text{Operational Readiness} + 9.377 \times 10^{-5} \times \text{Sense of Safety} \\ + 0.53909 \times \text{Sense of Time Savings} \dots \dots (3.7)$$

The null hypothesis can be tested to investigate whether any strong evidence is present in the data that explains the effect of explanatory variables on the mean response for performance. The null hypothesis statement is; the mean performance response does not change with the response of morale, operational readiness, sense of safety or sense of time savings; while the alternative statement was at least one of the coefficients is nonzero. This can be expressed as

Null hypothesis,

$$H_0: \beta_{\text{Morale}} = \beta_{\text{Operational Readiness}} = \beta_{\text{Sense of Safety}} = \beta_{\text{Sense of Time Savings}} \\ = 0 \dots \dots (3.8)$$

And alternate hypothesis,

$$H_a: \beta_{\text{Morale}} \neq \beta_{\text{Operational Readiness}} \neq \beta_{\text{Sense of Safety}} \neq \beta_{\text{Sense of Time Savings}} \\ \neq 0 \dots \dots (3.9)$$

During hypothesis test, the test statistics are compared with the t-distribution on n-5 (i.e. sample size – regression coefficient) degrees of freedom. Table 3.2 shows that the two tailed P-value for morale and sense of time savings is less than 0.01. This proves strong evidence for rejecting the null hypothesis that the mean response for performance does not change with the moral or sense of time savings response, while rest of the variables remain constant. However, we cannot reject the null hypothesis for operational

readiness and sense of safety as the P-value is greater than 0.15. This analysis indicates the strong influence of two specific mission benefit areas on the users' perspective towards performance. The regression analysis output is summarized in table 3.2.

Table 3.2. Regression parameter estimates for performance and remaining variables

Coefficient	Parameter estimate, β	T	P	VIF
Intercept	0.10632	0.58	0.5622	0
Morale	0.39024	2.67	0.0098	10.27
Operational readiness	0.05977	0.50	0.6209	8.93
Sense of safety	9.377e-5	0.001	0.9994	6.93
Sense of time savings	0.53909	4.60	0.0001	7.86

Presence of collinearity among explanatory variables might make it hard to find the predictive effect of each one on performance. Collinearity can be estimated from variance inflation factor (VIF). When the value of VIF exceeds 10, this indicates a strong evidence of collinearity in the explanatory variables. From table 3.2 it is observed that all the variables have collinearity. Morale is the one with severe collinearity. By selecting explanatory variable wisely, the variable with most predictive effect on response variable can be estimated. This can be done using the following some model selection criteria (R^2 , RMSE, C_p , AIC, SBC). From the summary of analysis, it is observed that three of the selection criteria among five choose two particular variables, which are morale and sense of time savings. This supports the result of hypothesis test achieved from earlier estimation. The model selection analysis is summarized in table 3.3.

Table 3.3. Explanatory variable selection for MLR model

Selection criteria	Cut off value	Variables in model
R ²	0.90	All variables
RMSE	0.34	Morale, Sense of time savings
C _p	5.00	All variables
AIC	-130.13	Morale, Sense of time savings
SBC	-119.96	Morale, Operational readiness and Sense of time savings

Using equation 3.7, performance response was predicted based on observed response of remaining variables using training set data. The predicted and observed performance response had a correlation coefficient, r of 0.95. Commonly the value of r ranges from -1 to +1, indicating negative strong response to positive strong response. The correlation coefficient of 0.95 indicates that the predicted performance response using the MLR model is very close to the observed response.

3.9 Conclusion

USC's attempt for better understanding of HUMS users' perspective involves using a Likert scale survey questionnaire and analysis of survey participants' attitude towards mission benefits that is, intangible benefits. By analyzing the response collected from a group flight and maintenance crews, who have used HUMS, it can be concluded that the attitude towards performance is mostly influenced by two factors, one is users' attitude towards how HUMS helps to increase their morale. And the other is sense of time savings formed in the users' mind by using HUMS. These two factors strongly correlate

with the attitude towards performance. As a result, when users think that HUMS is increasing their confidence during maintenance action and during flight and also helping to save time in maintenance, their attitude is found to be inclined towards performance improvement. This will help the leadership taking decisions in favor of HUMS deployment in broader scale knowing the users' feedback.

CHAPTER 4

ESTIMATION OF ECONOMIC EFFECTIVENESS OF HUMS EQUIPPED AH-64 AIRCRAFT USING ROI APPROACH

4.1 Benefits of CBM Practice

One of the pillars for CBM deployment is to monitor the operating condition of component of interest, collect data and analyze it to take necessary action. One of the prime reasons for preferring condition based maintenance over reactive and/or preventive maintenance, is the benefits (Bayoumi, A. et al., 2005). The benefits achieved can be divided into two broad categories: basic benefit and mission benefit (Vytautas, B. et al., 2009). A basic benefit stands for the benefits which are measurable in monetary value. For the Army Aviation case, basic benefit includes, but is not limited to maintenance man hour cost and replacement part cost. Monetary value of time savings due to CBM is also addressed as basic benefit. These time savings are calculated in forms of maintenance test flights (MTFs) cost, partially mission capable maintenance (PMCM) cost, not-mission capable supply (NMCS) cost, etc. On the other hand, there are some benefits which cannot be measured into monetary value, but their effect on CBM is undeniable. These benefits are addressed as mission benefits, or soft benefits: operation readiness, sense of safety, sense of time savings, confidence, morale, performance, etc. play a very important

role in CBM deployment. In this case study, the focus is on basic benefits to estimate the economic effectiveness of CBM practice

4.2 Measuring Economic Effectiveness

The assessment of economic effectiveness of CBM practice is nontrivial as it involves estimating benefits both in the form of monetary and non-monetary measures, combining them together and finally representing them in the form of a single indicator. In previous research attempts, either qualitative or quantitative measures have been considered, but the entire scenario cannot be understood by only looking into either of the measures alone. Studies show that there is a relationship present between cost of maintenance (COM) and cost of quality (COQ). Adaptation of the concept of COM and COQ may improve the effectiveness of maintenance function (Weinstein, L. et al., 2009). To increase the chance of a cost-effective CBM, clear instruction and regular practice is required (Al-Najjar, B. et al., 2012). Attempts are made to quantify the costs incurred and benefits generated due to CBM, both in the form of theoretical framework and case studies. A cost model is proposed for condition-based overhaul system where costs are described as a function of time or system status (Thorstensen, T. A. et al., 1999). Stochastic dynamic programming is used as a decision support tool in this model. In some research works, costs and benefits are described as lagging and leading indicators, respectively, which are key performance indicators (KPI). The proposed conceptual framework helps to choose KPI to improve maintenance performance (Muchiri, P. et al., 2010). In another study fuzzy logic and genetic algorithm (GA) are used as tools to assess and rank maintenance performance indicators to optimize maintenance performance

(Stefanovic, M. et al., 2015). All these studies are unique in their own way, but focus on quantifying either cost indicators or identifying the most effective one over maintenance performance.

Bayoumi et. al (2005) performed an annual cost savings analysis of the VMEP for AH-64 and UH-60 aircraft fleets, and the major findings of this study were presented in the forms of savings in part cost, operational support, increase in mission capability rates, decrease in maintenance, and increase in total flight time. The study also investigates the intangible benefits which include an increase in attention, performance, personnel morale, safety, sense of safety, and confidence for early diagnosis. With the continuation of the previous study, Bayoumi et. al (2009) also explored a larger timeframe to investigate the cost savings in a later study. The 8-year period with VMEP implemented showed a \$1.4M savings in parts costs and \$2.1M in parts and operational support cost. Later, Blechertas et. al performed another cost analysis for only AH-64 aircraft and presented the cost savings between two alternatives, baseline and VMEP. The results of this study indicate the improved ability of maintenance crews to adopt VMEP system by a decrease in maintenance test flight hours at SCARNG. Also, that a decrease in unscheduled maintenance actions and replacement parts costs are an indication of effective maintenance practice compared to the traditional practices. Army Aviation has a number of efforts focusing on gearbox repair, rotor blade repair etc., which demonstrate not only functional improvements but also cost effectiveness while utilizing CBM practice. However, the effect of overall paradigm shift towards CBM has not yet been estimated as a whole.

Army Aviation is in need of a CBA model to estimate the economic effectiveness of the CBM practice. This research work aims to propose a framework to calculate ROI and use Army Aviation historical data to validate the model and also evaluate the economic effectiveness of CBM implementation in SCARNG.

4.3 Data Overview

This study utilizes the data collected from Unit Level Logistics Systems-Aviation (ULLS-A), Unit Level Logistics Systems-Aviation-Enhanced (ULLS-AE), Document Control Registrar (DCR) and Federal Logistics data (FED LOG) to estimate the ROI for CBM practice in AH-64 aircrafts. ULLS-A and ULLS-AE, both represent multiple aircraft maintenance logbook forms and records among which Aircraft Status Information Record (2408-13) and Army Aviator's Flight Records (2408-12) are being used in this study (Department of Army Pamphlet 737-751, Army Regulation 700-138) Aircraft Status Information Record (figure 4.1) is used to enlist the faults occurred and corrective action taken for any aircraft. It also records if any aircraft is put into hold for unavailability of a required component which is needed for maintenance when the next scheduled maintenance and/or next special replacement/inspection is due. Along with the aircraft model type, the fault related information (i.e. fault description, aircraft status, system, date of the fault, fault code number, fault remark and the work unit code) was collected from the part I of the form. From part II, the correction information like the date the action was performed, and the action description are collected.

1. AIRCRAFT SERIAL NUMBER 8424235				2. MODEL AH-64A		3. DATE 27 AUG 93		4. PAGE 1	
PART I - FAULT INFORMATION					PART II - CORRECTING INFORMATION				
STATUS	SYS	DATE	NO	TIME	PID	DATE	TIME	ACFT HRS	WUC
	A	23AUG93		1200	6C9040	27AUG93	0900	834.8	
FAULTS/REMARKS R-60 PANEL HAS ONE NUT PLATE NOT INSTALLED					ACTION REENTERED TO DA FORM 2408-14-1				
ACFT HRS 830.8			WHEN DISC X	HOW REC G	MAL EFF 2				
DELAY REQ # 0036-0025			WUC 02		TI MANHOURS				
STATUS	SYS	DATE	NO	TIME	PID	DATE	TIME	ACFT HRS	WUC
		27AUG93		1000	BB9328				
FAULTS/REMARKS FLT 1 OK					ACTION				
ACFT HRS 834.8			WHEN DISC	HOW REC	MAL EFF				
DELAY			WUC		TI MANHOURS				
STATUS	SYS	DATE	NO	TIME	PID	DATE	TIME	ACFT HRS	WUC
	A	27AUG93		1020	6C9040	27AUG93	1700	834.8	
FAULTS/REMARKS RED MAIN ROTOR BLADE HAS DEBONDED AREA OF 30 SQUARE INCHES AT BLADE STATION 182.0					ACTION REPLACED RED MAIN ROTOR BLADE WITH S/N C10-1936 INSP OK Y. Mueller				
ACFT HRS 834.8			WHEN DISC Q	HOW REC G	MAL EFF 2				
DELAY 2408-13-2			WUC 05A02		TI MANHOURS 1.0				
ACFT HRS 834.8			WHEN DISC Q	HOW REC G	MAL EFF 2				
DELAY 2408-13-2			WUC 05A02		TI MANHOURS 1.0				
STATUS	SYS	DATE	NO	TIME	PID	DATE	TIME	ACFT HRS	WUC
	A	27AUG93		1020	6C9040	27AUG93	1700	834.8	
FAULTS/REMARKS RED MAIN ROTOR BLADE HAS DEBONDED AREA OF 30 SQUARE INCHES AT BLADE STATION 182.0					ACTION REPLACED RED MAIN ROTOR BLADE WITH S/N C10-1936 INSP OK Y. Mueller				
ACFT HRS 834.8			WHEN DISC Q	HOW REC G	MAL EFF 2				
DELAY 2408-13-2			WUC 05A02		TI MANHOURS 1.0				

DA FORM 2408-13-1, OCT 97
DA FORM 2408-13-1, OCT 91, MAY BE USED

AIRCRAFT INSPECTION AND MAINTENANCE RECORD
For use of this form see DA PAM 738-751; the proponent agency is DCSLOG

Figure 4.1: An example of Aircraft Status Information Record (2408-13)

An Army Aviator Flight Record (figure 4.2) is used for recording flight operations and limited maintenance operations. This form records aircraft flying time, duty symbols and type of flight accomplished by the pilot and crew. This is a permanent historical record for pilots and crew members which is used for pay purposes. DCR is a record for purchasing components for aircrafts. This record keeps track of the purchase request made and completed, the priority of purchase request, national item identification number (NIIN), order status, order quantity, etc. FED LOG is a software that can be used by various departments of Army Aviation, Coast Guard, US Navy, etc. to collect

replacement part information against National Stock Numbers (NSNs). In this study, FED LOG has been used to calculate extended price of replacement part by retrieving unit price of respective parts.

1. DATE 27 AUG 93		2. SERIAL NUMBER 8424235		3. MODEL AH-64A		4. ORGANIZATION C TROOP 1/6 CAV		5. STATION FT HOOD TX							
6. a. FLIGHT 1		DATA FROM LOCAL		TO		TO		TO							
TIME	FROM	TO	TO	TO	FLT HRS	LDG. STD	AUTO	STARTS #1	#2						
	06:00		10:00		4.0	6	0								
MISSION ID	STD	CONFIG	LOADS: INTERNAL		EXTERNAL	PASSENGERS		CYC	HSF						
ROUNDS	7.62	20mm	30mm	39	40mm	ROCKET	TOW		HELLFIRE 1						
STATUS	7.62	20mm	30mm		40mm	ROCKET	TOW		HELLFIRE						
HIT CHECK	NO. 1 ENGINE +1		NO. 2 ENGINE -1		APU: STARTS		HOURS	HOUR METER HRS							
b. 27 AUG 93 PERSONNEL DATA					c. DUTY SYMBOL/FLIGHT SYMBOL/HOURS/SEAT										
NAME	RANK	PID/SSAN		DS	FS	HR	S	DS	FS	HR	S	DS	FS	HR	S
JOHNSON, S.	CW3	SJ1071		PI	D	4.0	B								
BYRUM, B.	CW3	BB9328		Pc	D	4.0	F								
LAST ENTRY															
7. SERVICING DATA															
FUEL ADDED (GALLONS)	GRADE	IN TANKS	OIL 1	GRADE	OIL 2	GRADE	APU	GRADE	OXY-GEN	ANTI-ICING	SERVICED BY		LOCATION		
	JP4	300	7	23699	7	23699	2	23699			J. Huff		HOOD AAF, TX		
290	JP4	375	1	23699							T. Lisch		HOOD AAF, TX		
191	JP4	375									J. Huff		HOOD AAF, TX		
481			1										TOTALS		

DA FORM 2408-12, JAN 92
EDITION OF JAN 64 IS OBSOLETE

ARMY AVIATOR'S FLIGHT RECORD
For use of this form, see DA PAM 738-751, the proponent agency is DCSLOG

Figure 4.2: An example of Army Aviator's Flight Records (2408-12)

4.4 Assumption

1. From FY2000 to FY2006, SCARNG has been running the VMEP program using VMU as a CBM tool on AH-64A aircraft. From FY2007, the leadership started to use MSPU which is another form of VMU, in mostly AH-64D model aircraft. It is assumed that the aircraft will not be able to produce the expected savings right from

the moment the implementation starts. It is also assumed that it will take the first two years to get settled with the new system. So, from FY2009 to FY2013, the system will reflect the benefit of using CBM in those aircraft. For this reason, the 14-year time frame has been divided into three phases; the VMU-phase, the Investment phase, and the MSPU-phase.

2. Another reason for choosing a 14-year time frame is to account the true effect of CBM practice. Unit level maintenance logs and flight records are the two key sources to calculate time related cost. It has been observed from those records not every kind of phase maintenance is repeated in each fiscal year. This is applicable for unscheduled maintenance as well. To take various phase and unscheduled maintenance procedures into consideration, a longer time frame has been used rather than a single year.
3. ROI is calculated from two components: cost and benefit. In this case study, investment done for CBM practice is considered as cost. On the other hand, the difference of costs between VMU and MSPU-phase is considered as benefit. Considering the time value of money, all the cost is converted to the future value of FY2013 with a 3% inflation rate using the formula below:

$$F = P \times (1 + i)^N \dots \dots \dots (4.1)$$

Where F is the future value, P is the present value, *i* is the inflation rate and N is the period.

4. From FY2000 to FY2006, VMU was installed into AH-64A model aircraft and maintenance records are recorded though ULLS-A. During FY2007-FY2008, the leadership started to install the MSPU in AH-64D model aircrafts on a much larger

scale and records are kept using ULLSA-E. A distinct difference in aircraft performance has been observed after more widespread CBM deployment. In this case study, from FY2000 to FY2006 is addressed as the VMU-phase where CBM was practiced over a small number of aircraft. The later years, from FY2007 to FY2013 are addressed as MSPU-phase.

5. The investment is calculated in the form of equipment cost and man-hour cost for equipment installation. Such cost occurred in two stages, one is during VMU installation, and the other is during MSPU installation.

4.5 Method

In this study, both VMU and MSPU-phase cost is comprised of two sources: one is from direct cost and another is from the operating cost. The economic effectiveness of CBM deployment is measured from historical maintenance and unit-level logistic records and then expressed in terms of ROI, the ratio of return over investment. Direct cost and operating cost are calculated from the historical maintenance and unit-level logistics records. Investment cost is comprised of equipment cost and man-hour cost during installation phase. The ROI is calculated using the following expressions (2-6) where $C_{equipment}$, $C_{installation}$, $C_{VMU-phase}$ and $C_{MSPU-phase}$ represent various costs for investment and benefit. The details of sub-components of equation 4 and 5 are discussed in following sub-sections.

$$ROI = \frac{Benefit - Investment}{Investment} \dots \dots \dots (4.2)$$

$$\text{Where, } Investment = C_{equipment} + C_{installation} \dots \dots (4.3)$$

$$Benefit = C_{VMU-phase} - C_{MSPU-phase} \dots \dots \dots (4.4)$$

$$C_{VMU-phase} = \sum_{FY2000}^{FY2006} C_M + C_{MTFs} + C_{PMCM} + C_{NMCS} \dots (4.5)$$

$$C_{MSPU-phase} = \sum_{FY2007}^{FY2013} C_M + C_{MTFs} + C_{PMCM} + C_{NMCS} \dots (4.6)$$

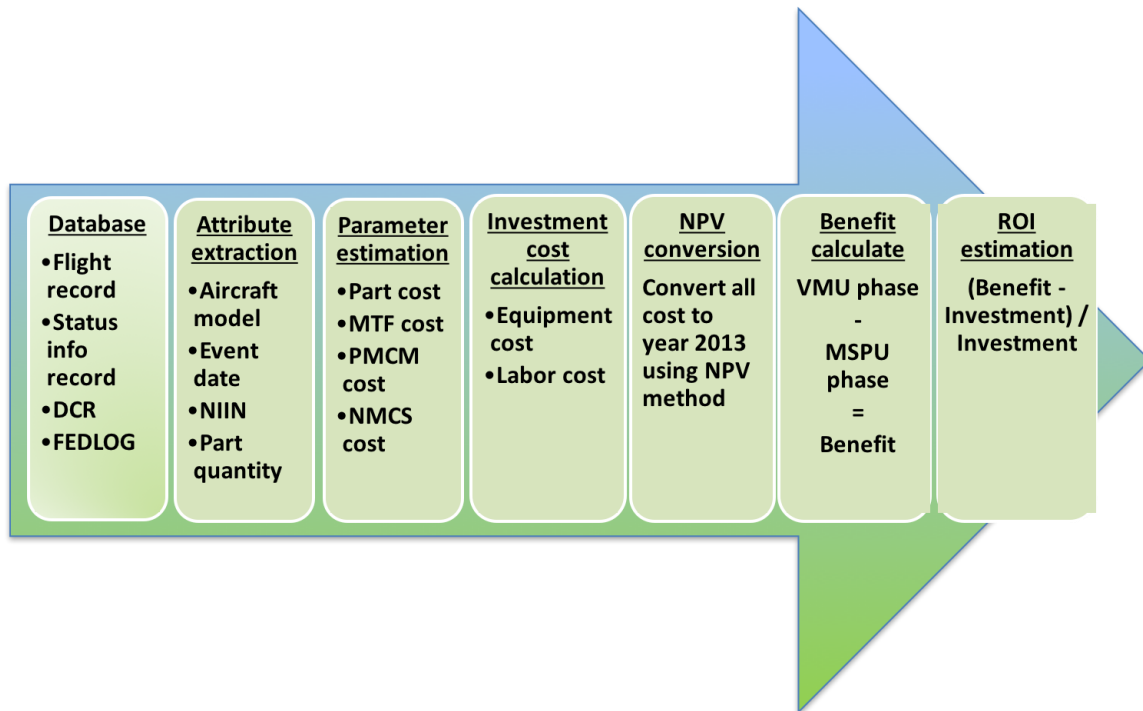


Figure 4.3: The method of ROI estimation using maintenance log and flight records

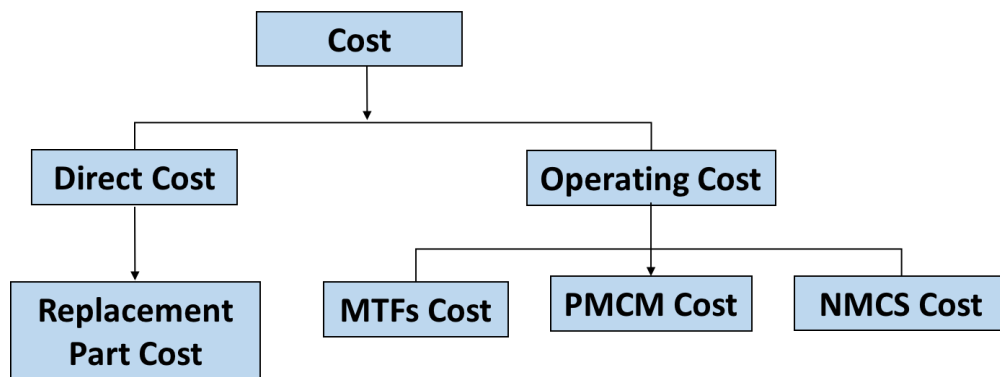


Figure 4.4: Cost classification

4.5.1 Direct Cost

Cost that is easily identifiable in a cost object or service is direct cost, which includes direct material and direct labor (Garrison, R. H., 2010). Direct material becomes an integral part in the final product and the related cost is traceable. Direct labor is the factory labor which is used for making the final product. Usually direct material cost is calculated from the material requisition form and direct labor is from the employee time log or time-ticket which keeps a record of daily hours.

In this case study, the point of interest is performance of Army aircraft, which makes it a service industry where the final product is the flight hour of aircraft in an active mission. Replacement part cost and maintenance man hour are two components which play a key role in overall maintenance cost. In this case study these two costs are referred to as direct material and direct labor respectively.

4.5.1.1 Replacement Part Cost

Replacement part cost is an integral part of maintenance cost which is incurred when a purchase requisition has been made and completed as the required parts for maintenance are unavailable in inventory. CBM practice tends to lower the rate of unscheduled maintenance event and increase the use of functional life of that component (Vytautas, B. et al., 2009). Such action leads to fewer requirements of replacement parts and thus reducing maintenance cost.

In this case study replacement part cost is calculated using DCR and FED LOG, which includes costs for purchasing materials or parts needed for maintenance. The attributes extracted from DCR used to calculate replacement part costs are

- Aircraft model
- Aircraft identification number
- Date of purchase order created,
- Current order status,
- National Stock Number (NSN) of that part, and
- Part quantity.

NSN is a 13-digit numeric code, used for identifying all the standardized material items of supply by United States Department of Defense (DOD). 13-digit NSN is comprised of 4-digits of Federal Supply Class (FSC) and 9-digits of National Item Identification Number (NIIN). NIIN is a unique identification number for every item of supply in the NATO Codification System (NCS). Unit price of each replacement part is collected from FEG LOG using NIIN.

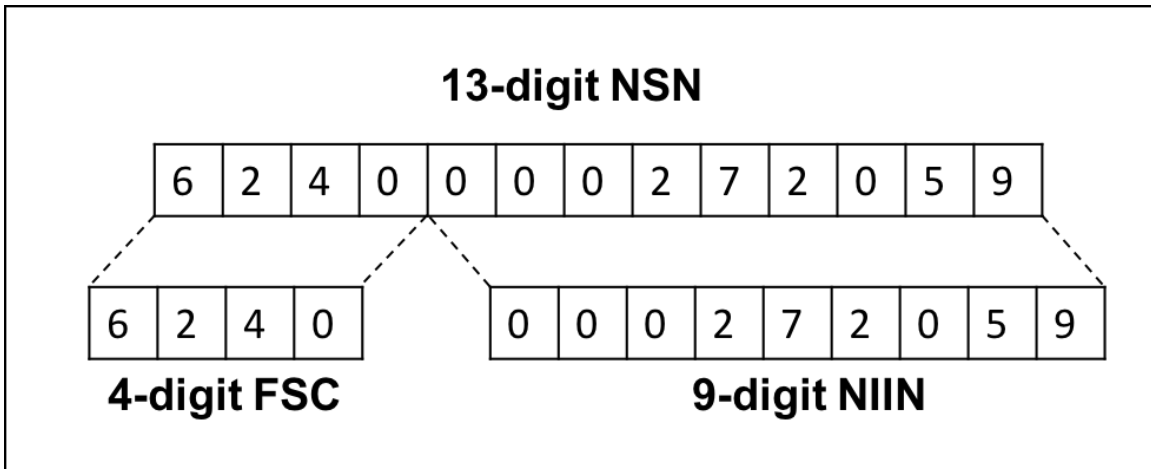


Figure 4.5: FSC and NIIN as sub-groups of NSN

For any specific year, all the AH-64 aircraft in active mission are considered for replacement part cost calculation. The status of the purchase request can be observed through its order status. The options used to describe order status are as follows:

- Available
- Awaited SARSS
- Cancelled
- Closed
- Closed cancelled
- Closed received total quantity
- Disapproved by tech supply
- Order approved external
- Ordered

For those, the order has been fulfilled, the order status is updated to ‘Closed’ or ‘Closed received total quantity’ and the required dollar amount is adjusted to the budget. If the part is available in the inventory or the request is disapproved, the order is made canceled and the order status is updated accordingly. Here, only closed cases has been considered for replacement part cost calculation. For every purchase request, the unit price of requested part is collected from FED LOG and then extended price is calculated. The replacement part cost per aircraft for every 100 flight hours in any year is calculated using the following expression:

$$C_M = \frac{\sum n \times C_P}{\sum FH} \times 100 \dots \dots \dots (7)$$

Where n represents part quantity, C_P represents unit price of that part, and FH represents the total possessed aircraft hours in any year. The entire procedure is then repeated for each aircraft to calculate the total replacement part cost.

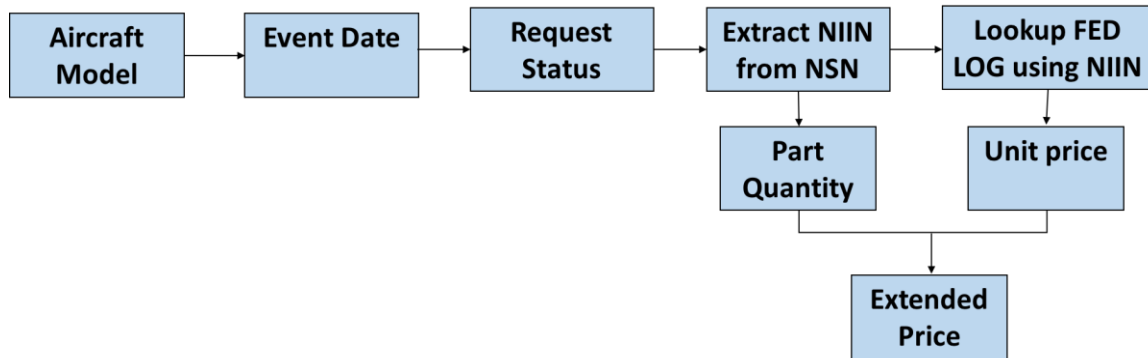


Figure 4.6: Replacement part cost calculation method

4.5.2 Operating Cost

Cost that is occurred from day-to-day operations in any product or service industry is referred to as an operating cost. In this case study, operating cost has been estimated from maintenance test flights (MTFs), partial mission capable maintenance (PMCM) and not-mission capable supply (NMCS).

4.5.2.1 Maintenance Test Flights (MTFs) Cost

One of the most demanding procedures of an active aircraft is to check periodically if all elements are performing well. This is ensured by performing maintenance test flight operations. MTFs cost are calculated from DA Form 2408-12 (Army Aviator's Flight Record), where flight hours are logged against specific flight type. Total flight hour is also calculated in the same way, only the distinction is that all kinds of flights are considered then. The procedure for MTFs hour estimation slightly varies depending on

the database. ULLS-A and ULLS-AE both have the following attributes which are used to calculate both FH and FH_{MTFs} .

- Aircraft model
- Event date
- Flight hour

In ULLS-A flight type is addressed as ‘Mission type’ where in ULLS-AE it is as ‘Duty symbol’. ULLS-AE has an additional feature ‘Seat’, which is absent in ULLS-A and this feature indicates the position of crew member in that flight. For AH-64 aircraft ‘F’ for front, ‘B’ for back is entered and flight hours are logged against each. To avoid redundancy in estimation either of the seat is selected. To calculate total flight hour, all kinds of ‘Mission type’ and ‘Duty symbol’ is considered. For maintenance test flight hour, only maintenance test flights are considered.

MTFs cost per aircraft for every 100 flight hour for any certain year is calculated using following expression:

$$C_{MTFs} = \frac{\sum FH_{MTF}}{\sum FH} \times C_{FH} \times 100 \dots \dots \dots (4.8)$$

Where FH_{MTF} represents the maintenance flight hours in any year and C_{FH} represents unit flight hour cost. The entire procedure is then repeated for each aircraft to calculate the total maintenance flight hours.

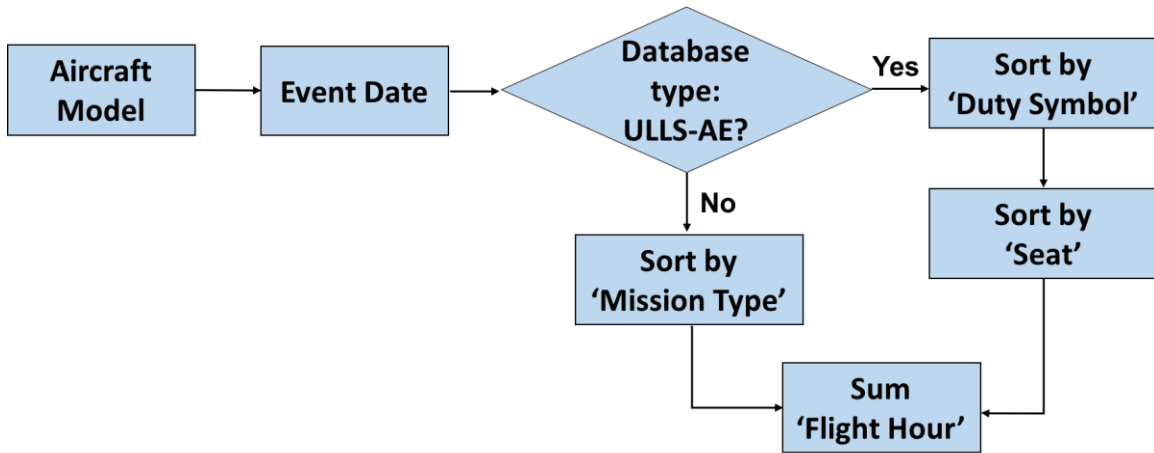


Figure 4.7: Flight hour (FH) and Maintenance flight hour (FH_{MTFs}) calculation method

4.5.2.2 Partial Mission Capable Maintenance (PMCM) Cost

Partial Mission Capable (PMC) is one of the metrics to measure equipment availability rates which can be caused by maintenance, supply unavailability, or both. During PMCM condition an aircraft is still operable, but under certain restriction. In an ideal case, 100% operational readiness is considered as 24 hours a day. The less the hour lost by PMCM, the more the operational availability will be achieved. Assuming an aircraft is inoperable for $\delta\%$ of a day, PMCM cost can be calculated for every aircraft using expression below:

$$C_{PMCM} = \frac{\sum D_{PMCM} \times 24 \times \delta\%}{\sum FH} \times C_{FH} \times 100 \dots \dots \dots (4.9)$$

Where D_{PMCM} represents the days in PMCM status in any year. Here, PMCM is calculated using DA form 2408-13 (Aircraft Status Information Record) and the following attributes extracted from it:

- Aircraft model
- Date of fault detected

- Date of corrective action taken
- Description of fault detected
- Description of corrective action taken, etc.

Both the descriptions of fault and corrective action are text-based fields. These fields contain information regarding reported faults or scheduled maintenance and corresponding maintenance actions. Most of the words are domain specific, in particular about aircraft parts and maintenance actions. These words also contain acronyms or abbreviations which are often addressed to individual or group of maintainers. In most of the cases, the descriptions do not constitute complete English sentences and do not follow grammar. Using open source Natural Language Toolkit (NLTK), records were detected when any aircraft was in PMC due to maintenance. From the date of fault detection and date of corrective action taken, the days in PMCM (D_{PMCM}) status was calculated.

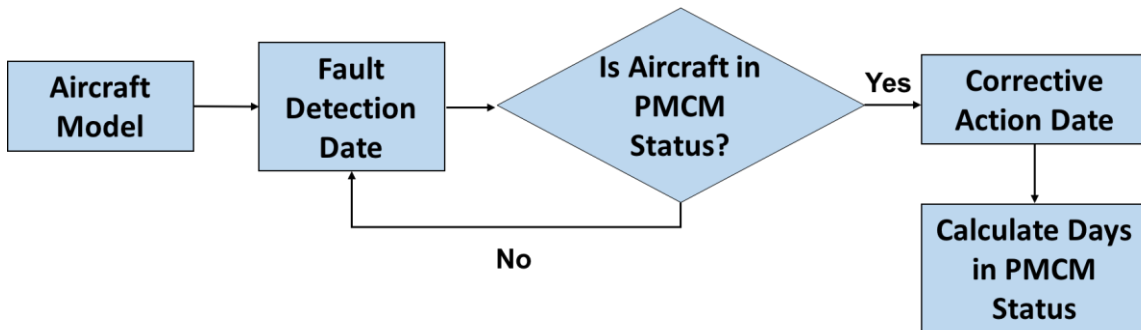


Figure 4.8: Days in PMCM (D_{PMCM}) status calculation method

4.5.2.3 Not-Mission Capable Supply (NMCS) Cost

Equipment non-availability rate is measured from different kinds of not-mission capable condition like NMC, NMCS, NMCM, NMCB, etc. Not mission capable condition can be the result of unavailability of required maintenance procedures, lack of

supply, or both. When an aircraft is not available due to lack of supply, the aircraft status is marked as Red-X in form 2408-13; indicating the grounded condition. The urgent need of that supply material is then synced with DCR by mentioning the priority of that requisition. Here, NMCS is calculated in days from DCR by looking up the priority of that request which has been completed. NMCS cost per aircraft for every 100 flight hour is calculated using following expression:

$$C_{NMCS} = \frac{\sum D_{NMCS} \times 24}{\sum FH} \times C_{FH} \times 100 \dots \dots \dots (4.10)$$

Where D_{NMCS} represents the days in NMCS status in any year.

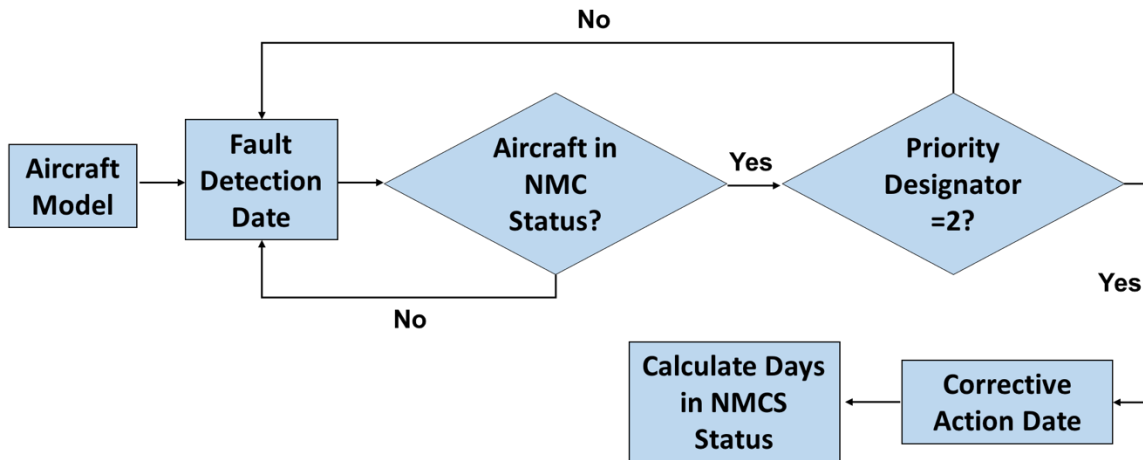


Figure 4.9: Days in NMCS (D_{NMCS}) status calculation method

4.6 Analysis

For the ROI estimation of a 14-year CBM practice in SCARNG, it has been observed that the number of aircraft active in a mission using HUMS as a mean of condition monitoring has been significantly increased. Figure 4.10 shows the change of aircraft over the years through a barplot. The average number of aircraft in the VMU-phase and MSPU-phase are shown using two horizontal dashed lines. The boost in CBM

practice in AH-64 aircraft is clearly visible from the vertical distance between two lines. On average, the number of HUMS equipped aircraft was increased by 270%.

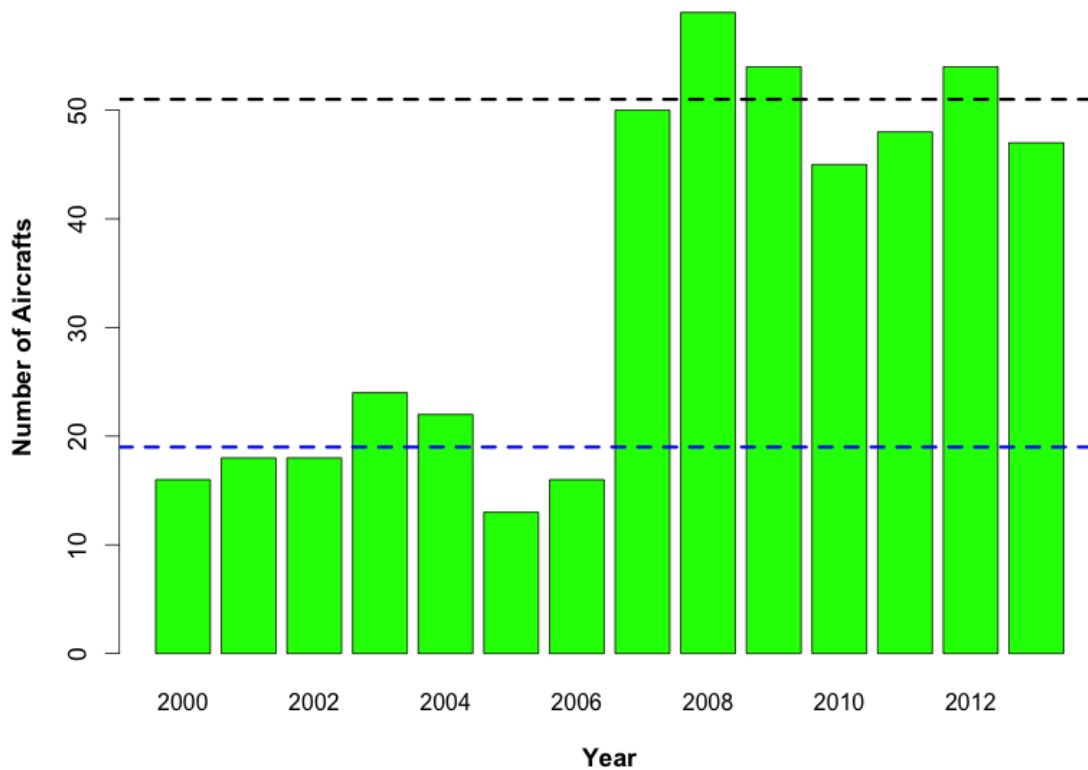


Figure 4.10: A graph showing the increase in the number of AH-64 aircraft which are active and use HUMS as condition monitoring system

As a consequence of increased active aircraft, the total flight hour over years also increased by 243% per aircraft from the VMU-phase to the MSPU-phase. The blue and black dashed line in figure 4.11 represent the average flight hour for VMU-phase and MSPU-phase respectively.

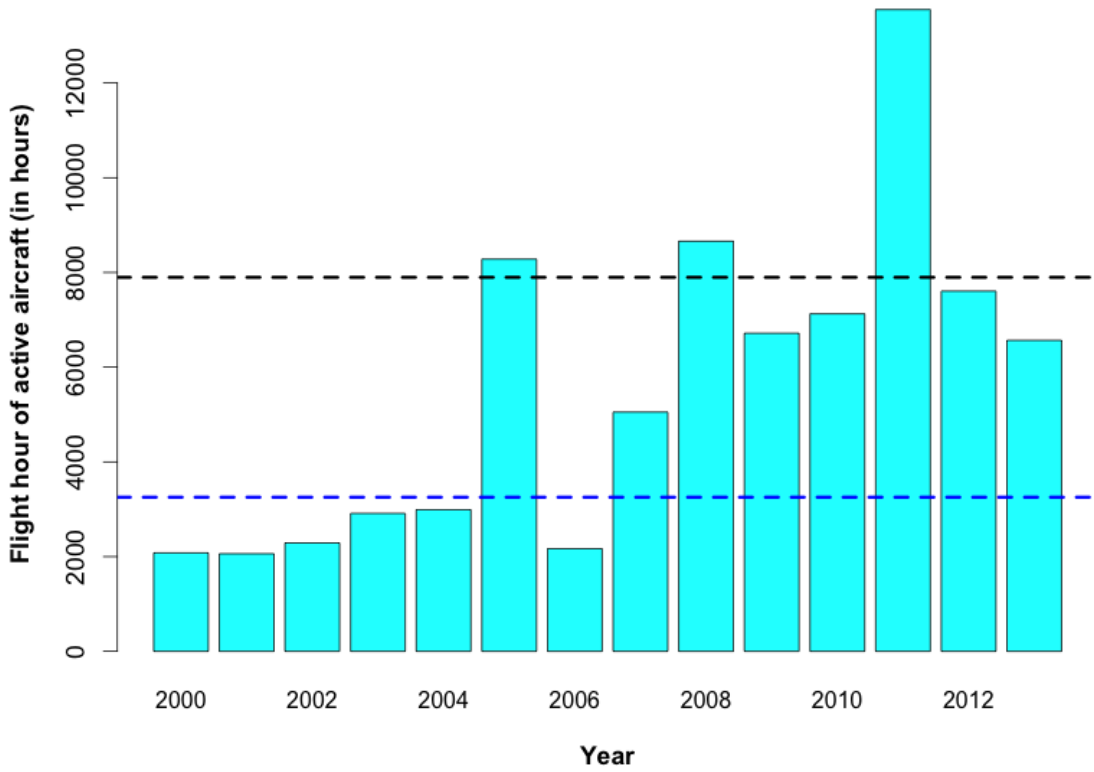


Figure 4.11: A graph showing the increase in total flight hours for AH-64 aircraft in active mission

For replacement part cost calculation, only the completed requisition request from DCR has been considered. In DCR, each part is identified by an 11 digit NIIN whose last 7 digits is known as NSN. Using NSN, the unit cost of that part is extracted from FED LOG and then the extended price of that part is calculated using equation 4.7. Each vertical bar in figure 4.12 represents the total cost in thousands of US dollars in that particular year spent for replacement part purchase.

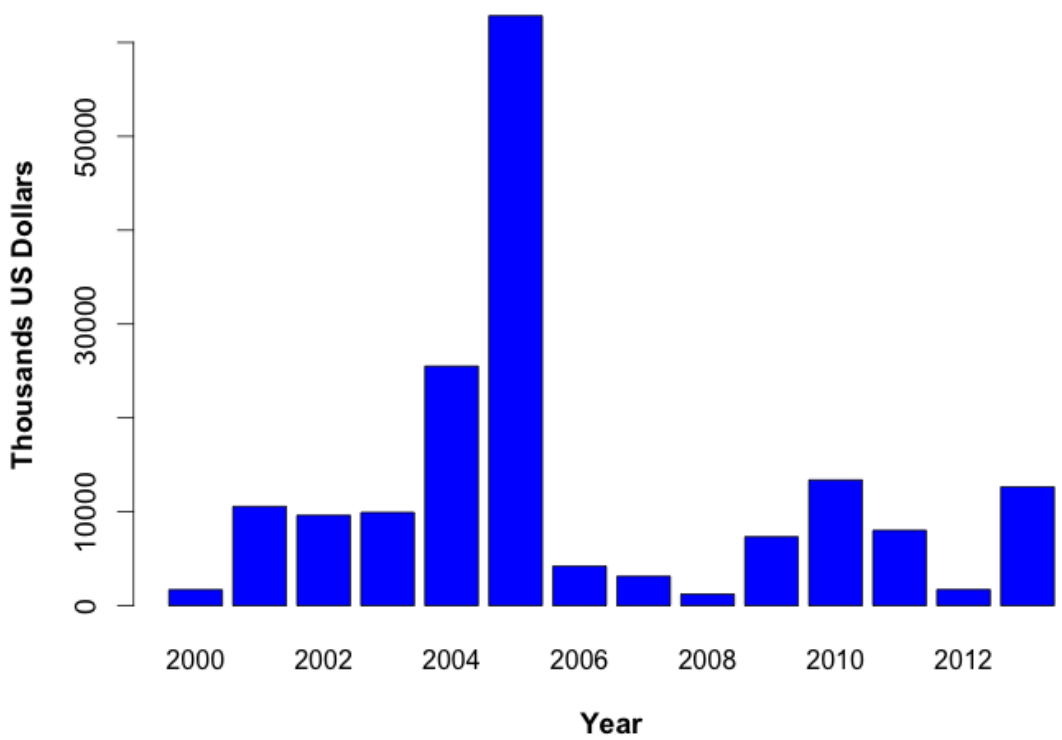


Figure 4.12: Replacement part cost estimated for respective years

Considering the inflation rate, all the part cost is first normalized by active aircraft and flight hour, then converted to the value of FY2013. In figure 4.12 the decreasing trend of replacement part cost over years is clearly visible. However, a sudden increase in replacement part cost in FY2005 which is normalized in figure 4.13. According to the data, in FY2001 the replacement part cost was the maximum over the 14-year period and the amount is 40K per aircraft for 100FH. The benefit thus calculated from the cost avoidance for replacement part cost per aircraft for 100FH over 14-year period is \$140K.

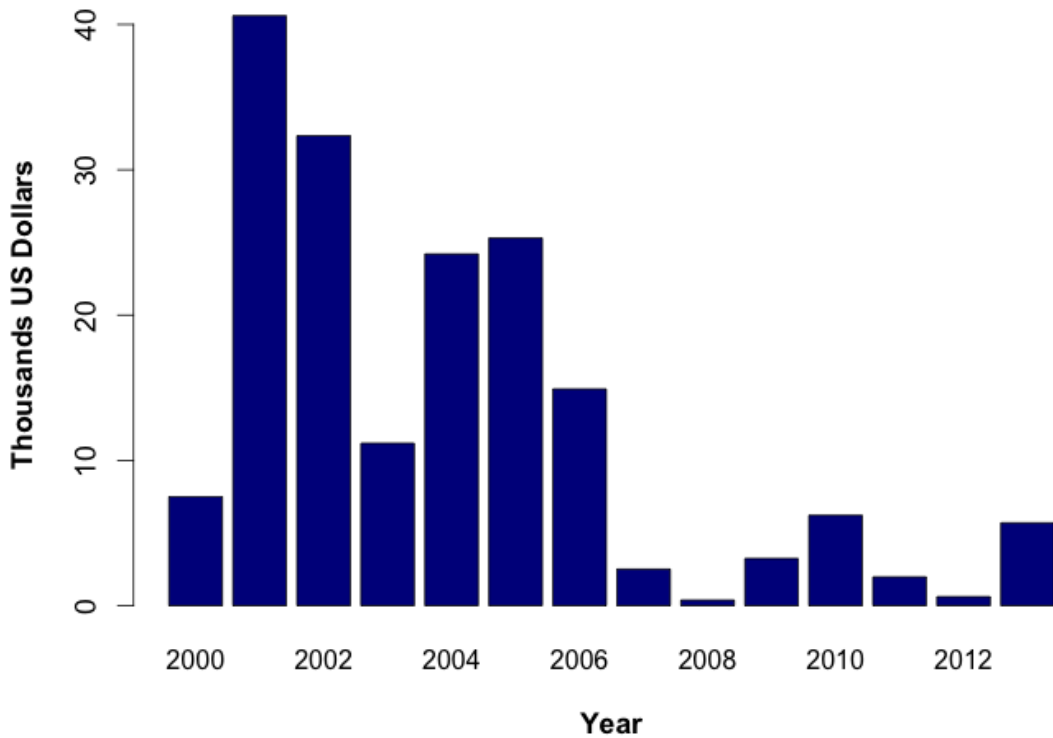


Figure 4.13: Replacement part cost converted to PV of FY2013 showing deceasing trend

Operating cost is calculated from MTFs cost, PMCM cost and NMCS cost using equation 4.8, 4.9 and 4.10. Table 4.1 summarizes the key parameters per aircraft to calculate the above mentioned costs. FH_{MTFs} denotes the flight hour for maintenance test flights and D_{NMCS} denotes the days for NMCS condition. In this case study, it is assumed that, an aircraft is inoperable for 20% of a day during PMCM condition. So, the column entitled “20% of D_{PMCM} ” represents the effective days in such condition. Like replacement part cost, each of the parameters is normalized as number of aircraft and flight hour vary year to year.

Table 4.1. Summary of parameters used to calculate related costs

FY	FH_{MTFs}	20% of D_{PMCM}	D_{NMCS}
2000	0.44	42.65	17.32
2001	1.47	20.68	17.17
2002	1.43	8.54	19.06
2003	0.63	5.53	24.27
2004	0.78	24.27	24.92
2005	0.50	4.01	69.01
2006	0.90	15.35	18.06
2007	0.05	38.75	42.09
2008	0.11	29.09	72.16
2009	0.16	40.76	55.96
2010	0.13	30.01	59.38
2011	0.08	19.40	92.12
2012	0.13	25.04	41.79
2013	0.10	2.29	29.22

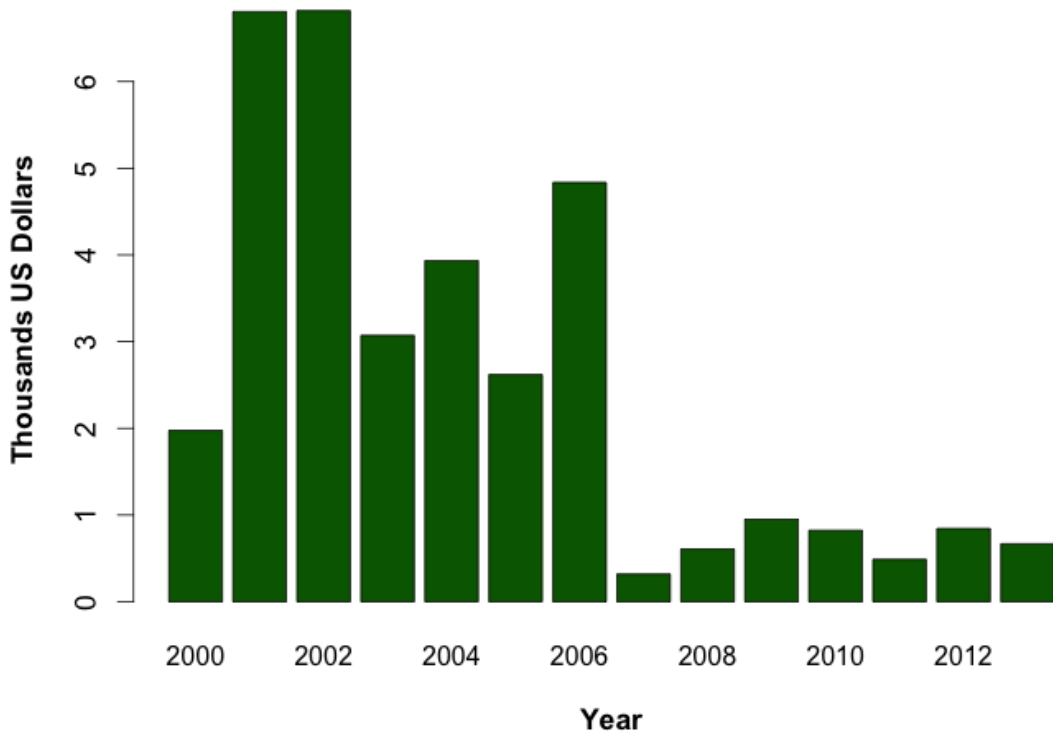


Figure 4.14: MTFs cost estimated and converted to FY2013 value

An important area for maintenance cost reduction is MTFs cost. The total MTFs hours for MSPU-phase are less than that of VMU-phase, which indicates time savings as a result of CBM practice. Figure 4.14 shows the decreasing trend of MTFs cost in thousands of US dollars per aircraft over time for every 100 hours flown. The overall benefit from reduction in MTFs over 14-year period is \$25K per aircraft for 100FH.

PMCM cost is one of the four cost metrics that are discussed in this case study. PMCM rate is also an indicator of aircraft readiness. A lower PMCM rate indicates a higher availability of aircraft for active mission. Here, PMCM rate is calculated in hours assuming that the inoperable rate for such condition is 20%. Figure 4.15 shows the

PMCM cost in thousands of US dollars per aircraft for 100FH over years. Overall the PMCM rate decreases over years except an increase during FY2007 and FY2009 which can be explained as an after effect of MSPU installation. Due to the price spike in these two years, overall the PMCM cost during MSPU-phase was increased and it costs \$1.03M per aircraft for 100FH over 14-years.

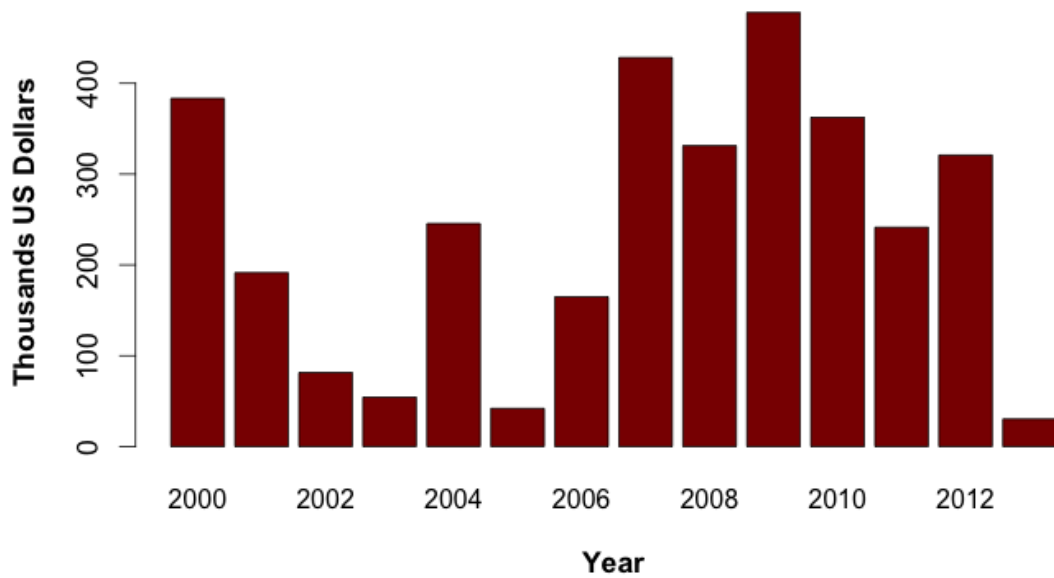


Figure 4.15: PMCM cost estimated and converted to FY2013

NMC is a condition when an aircraft is unable to perform due to interruption in maintenance or due to lack of supply. The hours lost due to NMC condition is addressed as NMC hour. For unscheduled maintenance the hour count starts when a malfunction is discovered or at mission completion, whichever occurs last. For scheduled maintenance, time is counted when the aircraft cannot be returned to mission capable status within 2 hours.

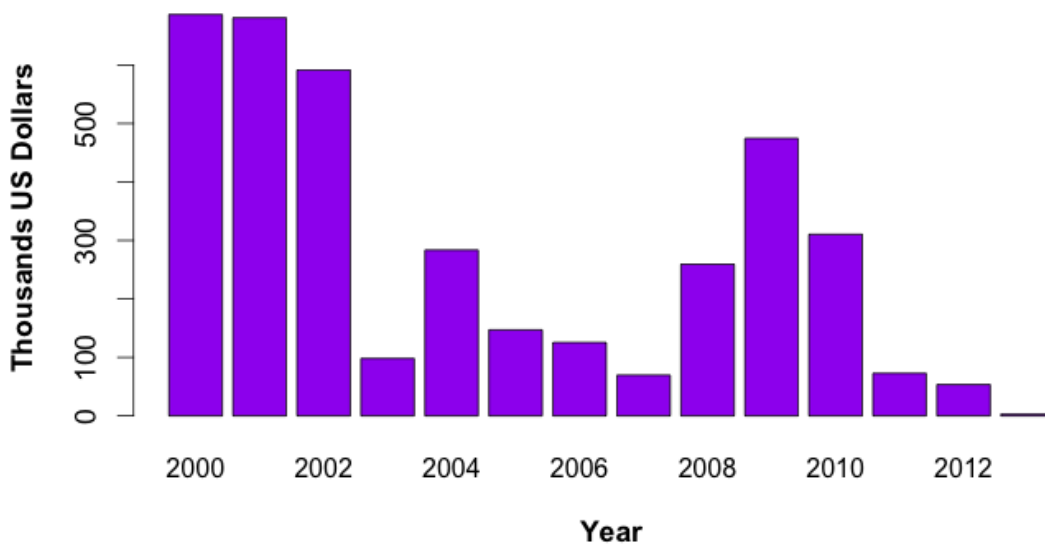


Figure 4.16 NMCS cost estimated and converted to FY2013

For both cases, time count is stopped when maintenance has been completed. Each of the vertical bar in figure 4.16 represents the cost occurred due to unavailability of aircraft due to supply. For first few years, the cost was high and it reaches up to \$650K per aircraft. But in later years the cost follows a decreasing trend which can be explained as an effect of CBM practice and less requirement for replacement parts. Over the year, NMCS cost decreases and a cost saving of \$1.37M per aircraft for 100FH is generated over 14-year.

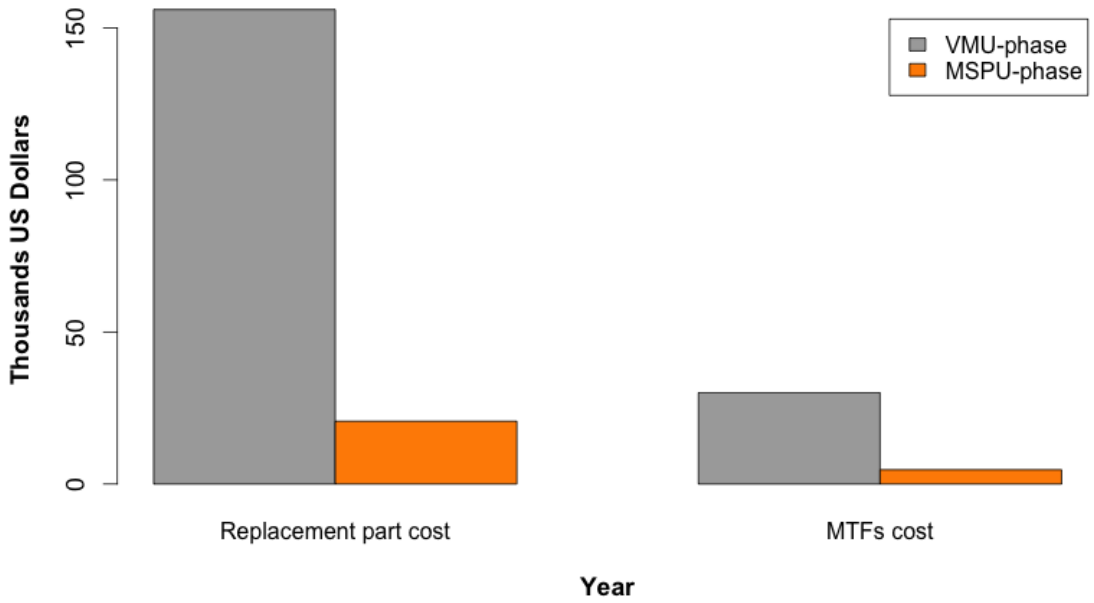


Figure 4.17: Comparison of replacement part and MTFs cost between VMU and MSPU-phase

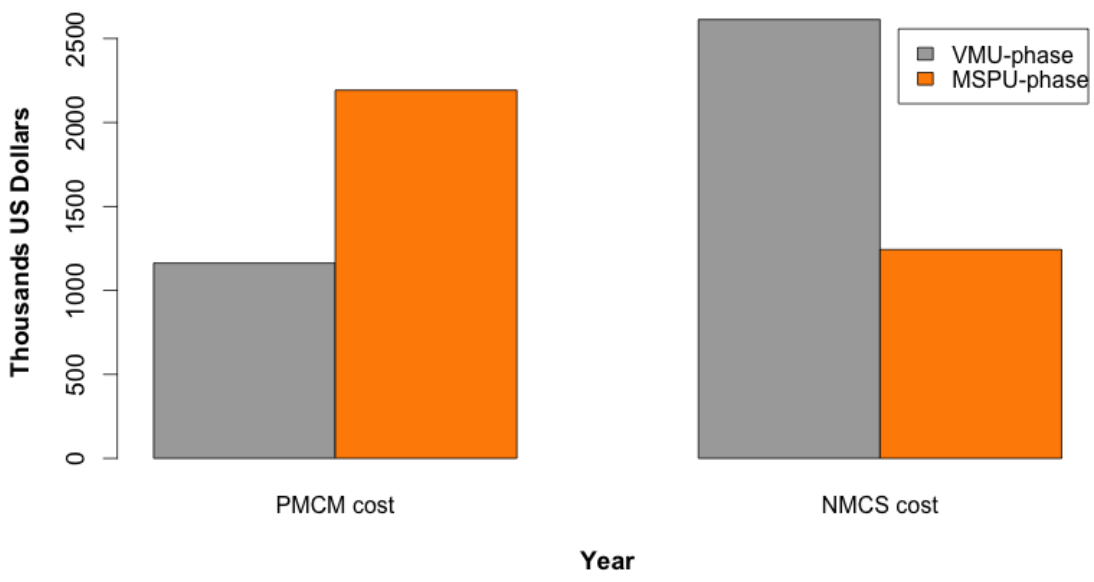


Figure 4.18: Comparison of PMCM and NMCS cost between VMU and MSPU phase

Figure 4.17 and 4.18 show a cooperative view of the cost avoidance generated for all the cost metrics between VMU and MSPU-phase. The comparison of cost is split in two different figures as cost avoidance for replacement part and MTFs cost are in thousands, whereas the latter two are in millions.

According to the historical usage data, 35 aircraft are active on average per year, which makes the direct cost benefit to \$5M and operating cost benefit to \$12.8M. When it comes to a single aircraft, direct cost benefit is \$140K and operating cost benefit is \$365K for 100FH over 14-year period. On the other hand, a total of 91 unique aircraft are equipped with HUMS during CBM practice in SCARNG which ends up in \$60K investment cost per aircraft. This results in 742% ROI per aircraft over a 14-year period.

4.7 Conclusion

From this study, it has been established that maintenance log and flight records are a reliable source of information to calculate cost and benefit of CBM practice. The benefit is calculated from four different metrics among which NMCS stands to be the largest source. It is also evident that in the long term both direct and operating cost tend to decrease at a significant rate. Compared to the generated returns, the investment cost is very negligible, which makes CBM a very effective maintenance practice.

CHAPTER 5

CONCLUSION

5.1 Summary

This dissertation was motivated to build the tools to evaluate tangible and intangible benefits of HUMS implementation and CBM practice in US Army. It is a very fundamental question to address when it comes to investment for new equipment and switch to a new practice than what is currently ongoing. Unlike anything in aviation, this on-board vibration monitoring equipment is expensive to purchase, install and maintain. But the cost savings achieved in return such as savings in part cost and operational support, increase in mission availability and total flight hour, decrease in unscheduled maintenance etc. are hard to ignore. Besides the tangible benefits, the impressive influence of improved maintenance practice on the working community makes HUMS an unavoidable addition to aviation industry.

In the first case study, a Likert-scale based survey responses have been statistically analyzed with an aim to reduce the survey response time keeping the accuracy unaffected. Maintainers, crews and pilots who are familiar with HUMS and also use the system to implement CBM methodologies, took part in that survey. The survey questions are designed to assess behavioral traits of the users towards the intangible

benefits like morale, operational readiness, performance, sense of safety and sense of time savings. Some of these questions are directly focused to a single intangible benefit indicator, some are focused to two or more. First, survey questions are grouped into five categories assuming that they are all focused to single benefit indicator at a time and the average response score for each of the benefit indicator was calculated. It has been observed that a linear increasing correlation exists between performance and each of the remaining intangible benefit indicator. Using 80% of sample data as test set, a multiple linear regression model has been proposed where performance is expressed as a function of morale, operational readiness, sense of safety and sense of time savings. While proposing the model, it has been statistically assessed that the sample follows normal distribution, the residuals have zero mean and have a constant variance. The hypothesis testing performed later also indicates that there is very strong evidence for morale and sense of safety towards performance. However, collinearity has been observed between performance and rest of the benefit indicators. Due to the presence of collinearity, it is hard to understand the predictive effect of benefit indicators over performance. The most influencing benefit indicator was identified from a comprehensive statistical analysis which agrees with the result of hypothesis test performed earlier. Finally, the proposed model was validated using a ten-fold cross validation using rest 20% of data as test set with a correlation coefficient of 0.95.

In second case study, a framework has been established to measure how well leadership can afford HUMS implementation and CBM practice. First, cost variables have been determined to measure the investment cost, direct cost and operating cost for a 14-year timeline of HUMS deployment and CBM practice on AH-64 aircraft in

SCARNG. The timeline has been divided into three phases: VMU-phase, MSPU-phase and investment phase. The investment cost includes equipment cost i.e. cost of HUMS and man-hour cost to install the system into aircraft. The direct cost is calculated in form of replacement part cost, while operating cost consists of maintenance test flight cost, partially mission capable maintenance cost and not-mission capable supply cost. All the cost variables for direct and operating cost are calculated using unit level maintenance log, flight records, document control register and FED LOG. All the data sources are heavily text-based information. An in-depth knowledge on aircraft maintenance is required to understand those records. NLP has been used for information extraction and interpretation. The benefit of HUMS deployment is then calculated from the cost savings in MSPU-phase to VMU-phase. The calculated ROI of 742% signifies the HUMS deployment and CBM practice in AH-64 aircraft as a success with a great margin of profit.

In general, the following conclusions can be drawn from this dissertation:

- Application of statistical techniques on Likert-scale based survey responses to develop a tool to predict the response for mission benefit, performance
- Application of NLP techniques on text-based maintenance and flight records to calculate direct and operating cost.
- Application of various engineering economy tool like NPV, ROI to estimate whether investment is worthy.

5.2 Future Recommendation

During the statistical analysis of survey responses, it has been assumed that each survey question is focused to single benefit indicator. But from the VIF value, it is clear that, collinearity is present between the independent variables addressed in the study. The effect of collinearity and the relation between the independent variables would be something interesting to investigate.

In the second case study, investment cost was calculated from equipment cost and installation cost. The cost for equipment upgrade, maintenance cost, personnel training cost was not considered here due to lack of information collected. Besides, maintenance man hour cost could be a great addition to direct cost while calculating cost savings. The PMC rate was assumed to be 20% to be conservative. Due to which cost savings was negative for this cost parameter. A dynamic PMC rate would be more justifies, as the system would get matured with time reducing unwanted PMC condition.

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