COST AVOIDANCE ANALYSIS OF MILITARY AIRCRAFT COMPONENTS UTILIZING CONDITION-BASED MAINTENANCE PRACTICES

by

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ABSTRACT

This research involves two major case studies. Both look at the current maintenance practices done by the United States Army and propose a solution for improvement utilizing condition-based maintenance (CBM) practices. Each study details a cost avoidance that can be earned by implementing the solutions and the resulting benefits that can be experienced.

Case Study I is a return on investment (ROI) that analyzes the benefits of the implementation of elastomeric wedges as vibration control on the Apache (AH-64D) aircraft. Analysis of the material and operational costs shows that the use of self-adhering elastomeric trailing edge wedges on the Apache helicopter in main rotor blade tracking operations will significantly reduce the number of blades damaged by tab bending that must be repaired at the depot level. Wedge implementation will also allow for a decrease in the number of test flights and maintenance man hours associated with those flights. Additionally, the wedges will lower aircraft vibration levels. A 10-year ROI is calculated for projected peacetime flying hours and for the current flying rate. Dollar values and flight hour optempo (operating tempo) have been removed and replaced with percentages or pseudonyms to comply with the operations security process.

Case Study II examines the maintenance practices regarding the GE T700, T701, T701C, and T701D turboshaft engine. According to the Aviation and Missile Command's (AMCOM) integrated priority list, the turboshaft engine is the number one cost burden to the Army with Army Working Capital Fund (AWCF) sales[a] exceeding $260M for FY12 and projected sales[b] over $200M for FY13. Analysis of Remediation/Reliability Improvement through Failure Identification and Reporting (RIMFIRE) data on engines determined to be field repairable by depot shows return of engine modules in lieu of the entire engine yields a significant cost avoidance. Returning modules instead of engines would reduce the number of field repairable engines sent to depot by almost 50%. Additional ways to reduce the number of field repairable engines are discussed and their benefits are included. Dollar values and component demand data have been removed and replaced with percentages or pseudonyms to comply with the operations security process.

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[a] Total AWCF Sales (last 12 months) is defined as "Dollar value of the AWCF sales for the last 12 months calculated by multiplying the AMDF price times the number of independent demands". The AMDF Price definition states "Also known as the standard price, it includes the latest acquisition cost plus the authorized cost recovery rate (surcharge)". Independent Demands are "the demands generated by a funded requisition from a retail unit".

[b] Projected AWCF Sales (next 12 months) is defined as "Dollar value of the AWCF sales for the next 12 months calculated by multiplying the AMDF price times the number of forecasted independent demands for the next 12 months".

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LIST OF ABBREVIATIONS

AED	Aviation Engineering Directorate
AMCOM	Aviation and Missile Command
AMRDEC	Aviation and Missile Research Development and Engineering Center
ASM	Accessory Section Module
AUP	Army Unit Price
AVIM	Aviation Intermediate Maintenance
AVSCOM	Army Aviation and Surface Material Command; now AMCOM
AVUM	Aviation Unit Maintenance
AWCF	Army Working Capital Fund
AWR	Airworthiness Release
CBA	Cost Benefit Analysis
CBM	Condition-Based Maintenance
CCAD	Corpus Christi Army Depot
CCH	Clogged Cooling Holes
CSM	Cold Section Module
DA	Department of the Army
EBR	Engine-Based Replacement
EPDM	Ethylene Propylene Diene Monomer
ERC	Exit Rub Combination
FEDLOG	Federal Logistics Data

FOD	Foreign Object Damage
FPG	Flight Pitch Ground
FR	Field Repairable
FY	Fiscal Year
GG	Gas Generator Matched Assembly
HUMS	Health and Usage Monitoring Systems
IETM	Interactive Electronic Technical Manual
IMMC	Integrated Material Management Center
IPS	Inches per Second
KTAS	or KTS; Knots, True Air Speed
LMP	Logistics Modernization Program
LRU	Line-Replaceable Units
MAC	Maintenance Allocation Chart
MBR	Module-Based Replacement
MFHBF	Mean Flight Hours Before Failure
MMH	Maintenance Man Hours
MMH/KFH	Maintenance Man Hours per 1000 Flight Hours
MR	Main Rotor
MSPU	Modern Signal Processing Unit
MTP	Maintenance Test Pilot
NATC	Naval Air Test Center
NCARNG	North Carolina Army National Guard
NSN	National Stock Number

O&S	Operations and Support
OSD	Office of the Secretary of Defense
PEOAVN	Program Executive Office Aviation
PM	Project Manager’s Office
PTM	Power Turbine Module
RIMFIRE	Remediation/Reliability Improvement thru Failure Identification & Reporting
ROI	Return on Investment
RS	Rotor Smoothing
RT&B	Rotor Track and Balance
SCARNG	South Carolina Army National Guard
SCV	Serviceable Credit Value
T/B	Track/Balance
TFP	Test Flight Pattern
UCV	Unserviceable Credit Value
ULLS-A	Unit Level Logistics Support - Aviation
USAF	United States Air Force
VMEP	Vibration Management Enhancement Program
VMU	Vibration Monitoring Unit

CHAPTER 1. INTRODUCTION

1.1 HUMS/CBM

In most industries, the Army included, maintenance is performed using a time-based system. This type of maintenance is best when used with initial designs. After failures are monitored and data is collected, these scheduled maintenance intervals can be adjusted. Unfortunately, this method is not ideal as it can lead to unexpected failures in critical parts, causing operational downtime and potential safety hazards. Due to this, it is "desirable to consider use-based maintenance practices so that critical parts are replaced or repaired before their full lifetimes on a variable basis balancing and optimizing both economic and safe operating conditions" [1]. With improvement to technology and the increase of the Army's information infrastructure, many aircraft have been outfitted with Health and Usage Monitoring Systems (HUMS). With the arrival of these on-board monitoring systems, maintainers have access to a near real-time assessment of component health [2]. HUMS utilizes condition-based maintenance (CBM) concepts to minimize unscheduled failures and maintenance costs. As defined by the Office of the Secretary of Defense (OSD), CBM is a "set of maintenance processes and capabilities derived, in large part, from the real-time assessment of weapon system condition obtained from embedded sensors and/or external tests and measures using portable equipment." Using data acquired from HUMS, incipient problems are identified and corrective actions are taken to improve the reliability, availability, and maintainability of the aircraft [3].

1.2 VMEP Project

One type of HUMS employed by the Army was implemented through a project known as Vibration Management Enhancement Program (VMEP). Via this government-industry-academia cooperative, the goal was to reduce the number of maintenance test flights, minimize aircraft operation and support costs, augment aircraft availability, and increase safety through in-flight vibrations monitoring, on-line data processing and artificial intelligence based decisions. Within the VMEP system, rotor smoothing (RS) "as well as vibration collection and surveying are fully supported, including the monitoring of all sensors for capture of exceedances (high condition indicators)" [4]. Succeeding the implementation of the vibration monitoring unit (VMU) in various aircraft, the University of South Carolina set out to provide an annual cost savings analysis of VMEP as well as create a cost benefit analysis (CBA) model through the correlation of vibration signals and the Unit Level Logistics Support-Aviation (ULLS-A) database. The CBA model utilizes test flight data from ULLS-A "in order to estimate a cost savings and recovery of the initial cost of the VMU hardware installation and future cost savings for the Apache and Blackhawk helicopters" [5]. The model includes cost variables such as: VMEP investment, test flight hours, cost per flight hour, hours per flight, number of VMEP helicopters, RS flights, non-RS flights. It also considers non-tangible variables including: morale, availability, operational flight hours' gain, mission aborts, safety, unscheduled maintenance occurrence, and premature parts failure. Non-tangible benefits were measured by tabulating responses based on an administered questionnaire. The findings from the results conclude that VMEP increases confidence in early diagnosis, increases confidence overall, increases attention to and concentration on mission and performance, increases morale, increases the sense of safety, and improves performance. As of the date the paper was presented, a savings in parts costs of $1.4M has been achieved as well as a savings in parts cost and operation support of $2.1M. Mission capability rates were increased through a decrease in maintenance test flights and an increase in total flight time [5].

1.3 Overview

Above all, CBM efforts provide an overwhelmingly beneficial experience for the military and any other organization that employs it. This research provides two major case studies that illustrate the potential for significant payoff accomplished by utilizing CBM practices. Both cases are introduced with background information relevant to understanding the existing problems. Following this, the current and proposed maintenance changes are described. Next, each study details a material and operational cost avoidance that can be earned by implementing the proposed maintenance improvements and the resulting benefits that can be realized. Additional benefits are discussed and suggestions for future work are given. Lastly, the case studies are summarized to highlight the essential points.

Case Study I is a return on investment (ROI) that analyzes the benefits of the implementation of elastomeric wedges as vibration control on the Apache (AH-64D) aircraft. Analysis of the material and operational costs shows that the use of self-adhering elastomeric trailing edge wedges on the Apache helicopter in main rotor blade tracking operations will significantly reduce the number of blades damaged by tab bending that must be repaired at the depot level. Wedge implementation will also allow for a decrease in the number of test flights and maintenance man hours associated with those flights.

Additionally, the wedges will lower aircraft vibration levels. A 10-year ROI is calculated for projected peacetime flying hours and for the current flying rate. Dollar values and flight hour optempo have been removed and replaced with percentages or pseudonyms to comply with the operations security process.

Case Study II examines the maintenance practices regarding the GE T700, T701, T701C, and T701D turboshaft engine. According to the Aviation and Missile Command's (AMCOM) integrated priority list, the turboshaft engine is the number one cost burden to the Army with Army Working Capital Fund (AWCF) sales[c] exceeding $260M for FY12 and projected sales[d] over $200M for FY13. Analysis of Remediation/Reliability Improvement through Failure Identification and Reporting (RIMFIRE) data on engines determined to be field repairable by depot shows return of engine modules in lieu of the entire engine yields a significant cost avoidance. Returning modules instead of engines would reduce the number of field repairable engines sent to depot by almost 50%. Additional ways to reduce the number of field repairable engines are discussed and their benefits are included. Dollar values and component demand data have been removed and replaced with percentages or pseudonyms to comply with the operations security process.

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[d] Projected AWCF Sales (next 12 months) is defined as "Dollar value of the AWCF sales for the next 12 months calculated by multiplying the AMDF price times the number of forecasted independent demands for the next 12 months".

CHAPTER 2. CASE STUDY I

2.1 Background

In 2010, the Vibration Control project began with one goal of improving the main rotor (MR) blade tracking feature used in helicopter main rotor smoothing. Routinely scheduled maintenance events use rotor smoothing (RS), also known as rotor track and balance (RT&B), to make corrective adjustments to pitch links, blade weights, and trim tabs with the use of Modern Signal Processing Unit (MSPU) equipment and procedures. Helicopter rotor smoothing is a complex process, requiring precise adjustments to a rotor system that has many dynamic forces in play [6]. The purpose of these adjustments is to improve the track of main rotor blades and determine their sensitivities, which reduces vibrations at the fundamental (once-per-revolution) rotor frequency. Alternatively, applying main rotor wedges can be used to reduce vibration instead of bending tabs. Helicopter main rotor wedges can be thought of as a more complex version of a balancing kit that can be purchased for a ceiling fan with wobbling blades. Reducing these vibrations increases the “smoothness” of aircraft flight. Lower vibration levels also result in a reduction in crew fatigue and a service life extension for both the airframe and installed components [6]. Current maintenance procedures prescribe bending metal tabs, which extend off the trailing edge of the main rotor blade, to a specified angle [7-9]. Tabs are bent using a tab bending tool, also known as a trim tab tool. A diagram displaying the tab bending operation can be seen in Figure 2.1, where KTAS stands for “knots, true airspeed”, sometimes written KTS.

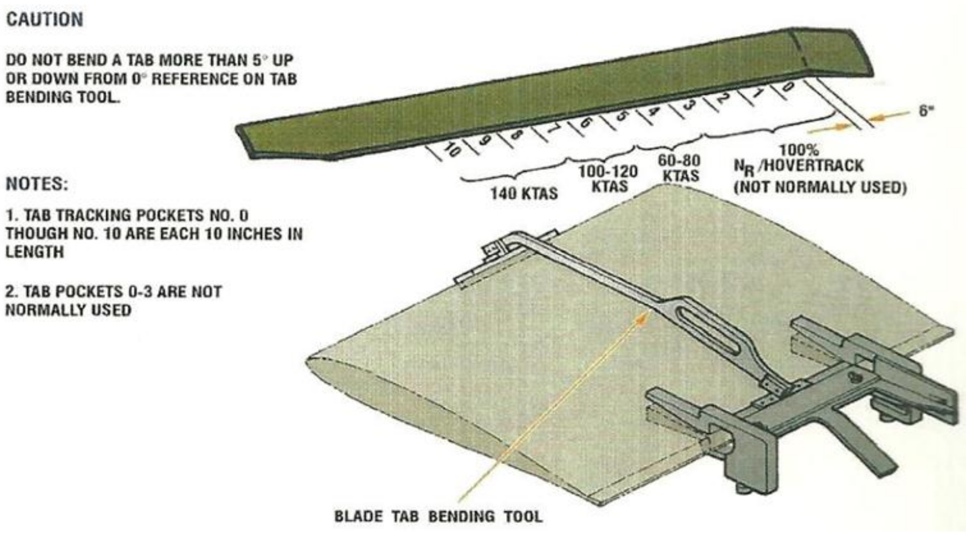

Figure 2.1: Diagram of Main Rotor Blade Tab Bending Tool Operation [10]

2.1.1 Current Procedure: Trim Tab Bending

The trim tabs are effective at achieving acceptable vibration and satisfactory blade track but put excessive burden on maintainers by requiring several maintenance test flights for adjustments as well as frequent adjustments over time to maintain low vibration levels. The trim tab tool only fits in one pocket at a tab so rotor balancing can get to be time intensive. Furthermore, trim tab adjustment can damage the blade, requiring blade replacement. In flight, the highest strain levels of any blade location are experienced along the trailing edge of the main rotor blade [9]. Bending the tab causes further strain along the bend, resulting in compromised material strength. This compromised strength means that the metal tab is subject to movement, both over time and as a result of blade flexing during flight, leading to degradation in rotor track and vibration [11]. All of this leads to trim tab washout, which means that the blade can no longer hold the angle required for rotor smoothing. Trim tab washout is a leading cause of increased vibration values over time. Washout is also experienced due to high gross weights and high airspeeds [6]. A certain skill is necessary when using the tab bending tool, a skill that is not taught to every maintainer. An inexperienced maintainer could easily exceed the maximum bend limit of 5° if not properly trained, resulting in blade damage beyond reparable limits. Consequently, RT&B actions could be delayed by an absence of trained maintainers. Even if the tab bending process is performed by an experienced maintainer, "trim tab angles are often applied inconsistently due to the inherent design of the trim tab bender, trim tab stiffness differences, and individual maintainer bending techniques" [6]. Repeatability of the angle change is another issue since the magnitude of the required adjustment is often very small. A limited quantity of trim tab tools is provided to each unit; therefore, maintenance could also be hindered by a lack of tool availability. The MR wedges will be implemented to recreate the trim tab's success in reducing vibration while decreasing maintenance time and MR blade demand.

2.1.2 Alternative Procedure: Wedges

Boeing designed self-adhering elastomeric wedges to improve the vibration and blade tracking over the helicopters full speed range while improving the current method of adjustment in a field environment. The tracking wedges have a peel and stick adhesive backing and are made of Ethylene Propylene Diene Monomer (EPDM) elastomer, which was chosen for its high resistance to chemical and environmental exposure. The relatively soft elastomer with low stiffness offers three major advantages: (1) it significantly reduces the adhesive demand allowing for the use of a pressure sensitive adhesive system in lieu of epoxy, which can result in permanent damage to the blade or wedge upon removal; (2) low stiffness means facilitated removal making the process similar to peeling tape from a flat surface; (3) to facilitate length adjustment since it can be cut with hand scissors [11]. Wedge kits include a piece of Scotchbrite pad, two alcohol wipes, and one 10.0-inch long, 1.25-inch wide wedge with a thickness angle taper of 6° [9]. A photograph of wedges installed on a MR blade can be seen in Figure 2.2.

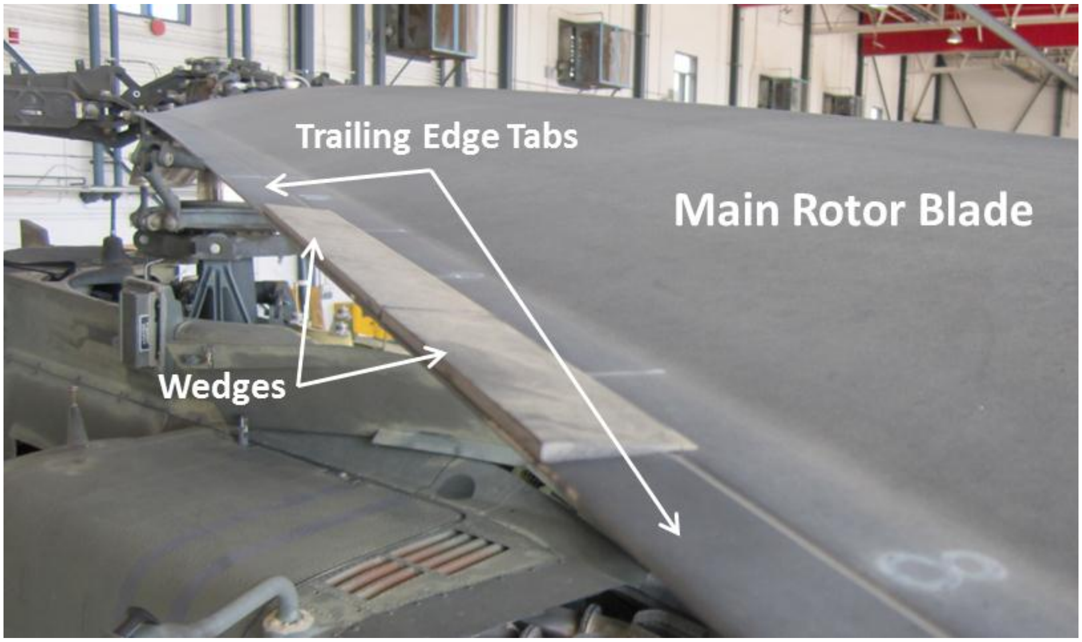

Figure 2.2: Photograph of Wedges on an AH-64D Main Rotor Blade (Courtesy of 1-151 ARB)

The addition of discrete main rotor wedges to the trailing edge of the main rotor blades allows for the same change in lift and pitching moment characteristics of the airfoils as experienced by trim tab deflection. Another immediate benefit is that flight test mechanics have found the MR wedge installation to be quicker, easier, and more precise as compared to bending trim tabs [9]. Moreover, trim tab washout will be eliminated since the blades are no longer required to be bent to a specific angle. The simple nature of the wedge design allows for a greater degree of adjustment to vibration and track through a wider range of airspeed that tab bending cannot provide consistently. It should also be noted that after accumulating hundreds of hours of flight time on a helicopter, none of the wedges failed or showed signs of significant peeling. These flight hours were performed on a variety of helicopters at typical speeds and altitudes in a variety of weather conditions for extended periods of time [11].

MR wedge installation is guided by the instruction of the MSPU system. A simple correlation is established for the appropriate amount of wedge based on MR trim tab bend requirements from the MSPU system [9]. The wedge equivalence to tab bends is listed in the wedge airworthiness release (AWR) and an overall correlation from that document for wedges and tab bends is shown in Table 2.1.

Table 2.1: Tab Bend and Wedge Equivalence [9]

Tab Bend (deg.)	Equivalent Wedge Length per Pocket (in.)	Total Wedge Length, Pockets 4-10 (in.)	Total Wedge Length, Pockets 6-10 (in.)	Total Wedge Length, Pockets 8-10 (in.)
0.5	1.0	7	5	3
1.0	2.0	14	10	6
1.5	3.0	21	15	9
2.0	4.0	28	20	12
2.5	5.0	35	25	15
3.0	6.0	42	30	18
3.5	7.0	49	35	21
4.0	8.0	56	40	24
4.5	9.0	63	45	27
5.0	10.0	70	50	30

A 3.0° bend in pockets 4-10 would mean that each individual pocket would need to be bent 3.0°; since the tab bending tool fits only in one pocket at a time, this task will be time consuming. With wedges, that same 3.0° bend simply means that 42 inches of wedge must be applied on the blade in pockets 4-10. The wedge AWR explains, “The shaded areas represent conditions for which there may not be enough real estate for the wedges. If the adjacent pockets are available, wedges may be added to the pockets immediately inboard or outboard.”

2.2 Analysis

Material and operational costs are examined to ultimately determine the return on investment after 10 years with the implementation of the MR elastomeric trailing edge wedges. The projected annual savings, or benefits, determined in the following analyses are taken as a cost avoidance in that these are costs that will not be spent on maintenance, but on training or missions. The material cost avoidance explores the costs associated with main rotor blade demand, while the operational cost avoidance considers the maintenance-related costs. The ROI incorporates the benefits from both the material and operational cost avoidances.

2.2.1 Material Cost Avoidance

Material costs are developed from Aviation and Missile Command (AMCOM) Integrated Material Management Center (IMMC) and Aviation and Missile Research Development and Engineering Center (AMRDEC) total return and demand data for MR blades.

2.2.1.1 MR Blade Material Demands FY09 – FY11

The analysis begins by acquiring the total demand for AH-64D MR blades from FY09 to FY11 which is used to then obtain an average MR blade demand. The values in Table 2.2 are taken as a percentage of the average annual MR blade demand. The total demand data for FY09 (60.35%) is significantly lower than the total demand data for FY10 and FY11 (132.81% and 106.84%, respectively). Due to a changeover in AMCOM Logistics Modernization Program (LMP) procurement systems, the demand for the entire FY09 year was not able to be accessed; the demands are only from 14 May 2009 to 20 Sep 2009. These values are not used to create a predicted annual demand due to an abnormal spike in demand during that time. The resulting values from this absence in data just provide a more conservative value than what would have been determined otherwise.

Table 2.2: AH-64D Main Rotor Blade Demands for FY09 – FY11 in AMCOM LMP[e]

Main Rotor Blade National Stock Number (NSN)[f]	FY09 Total MR Blade Demand[g]	FY10 Total MR Blade Demand[g]	FY11 Total MR Blade Demand[g]
MR Blade 1	60%	138%	102%
MR Blade 2	56%	75%	169%
MR Blade 3	72%	116%	112%
MR Blade 4	45%	85%	170%
Total:	**60%**	**133%**	**107%**

2.2.1.2 MR Blade Field Returns to Depot

Based on historical maintenance data, it is implied that trailing edge failures are related to tab bending. According to the team leader for the Aviation Engineering Directorate (AED) Maintenance Division at Corpus Christi, TX, the number of blades that are rejected for damage to the trailing edge beyond reparable limits is equivalent to 35.64% of the average annual MR blade demand.

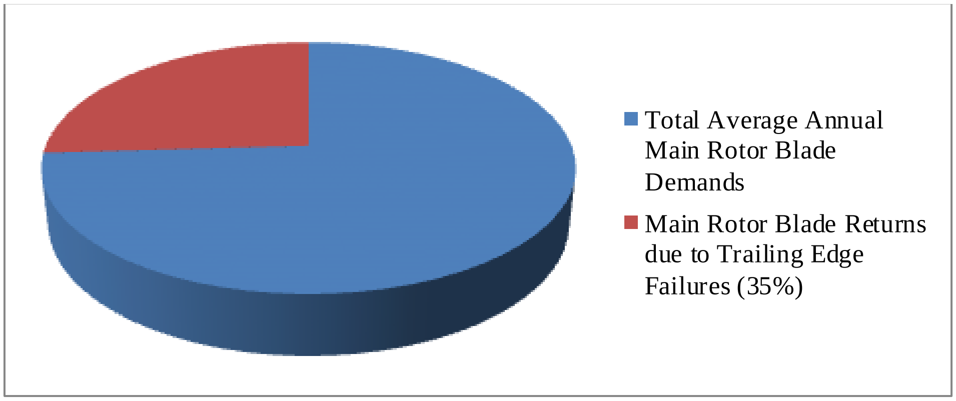

Figure 2.3: Pie Chart of Annual MR Blade Demands and Trailing Edge Failures

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[e] Values taken as a percentage of the average annual MR blade demand
[f] CSM Woody Sullivan; Department of the Army (DA) Form 2408
[g] Sara D. Finigan; AMCOM IMMC Item Manager for MR Blade

Figure 2.3 is a graphical representation of the MR blades that will be affected by wedge implementation. The number of MR blades with trailing edge failures will decrease with the use of wedges and it is what the material costs focus on.

2.2.1.3 Material Costs Prior to Wedge Implementation

Using the average annual MR blade demand, the unit price for the MR blade, and the percentage of MR blade returns due to trailing edge failures, the material costs prior to wedge implementation can be calculated. For this analysis, 35% is used for the MR blade returns that are due to trailing edge failures in order to obtain a more conservative value.

2.2.1.4 Material Costs After Wedge Implementation

Total flight hours for FY09, FY10, and FY11 are averaged together to find the current annual flight hour rate. In order to determine the material costs after wedge implementation, a peacetime estimate of flight hours is considered. It is anticipated that the United States will not always be at war and this should be reflected in the analysis. Values used in the subsequent calculations are taken as a peacetime-reduced percentage of the previously mentioned rate. Table 2.3 lists these projected rates as a percentage of the current rate.

Table 2.3: Projected Peacetime-Reduced Flight Hours as a Percentage of Current Flight Hours

	Percentage of Reduction
Projected Rate 1	42%
Projected Rate 2	50%
Projected Rate 3	63%
Projected Rate 4	75%
Current Rate	100%

It is expected that, with the change from tab bending to wedges, fewer blades will be returned due to trailing edge failures, resulting in a reduced demand. An estimated reduced demand rate of 25% is anticipated, another conservative value. The reduced demand rate means that 75% of that value will remain and will continue to be demanded. This rate is applied to the annual cost of MR blades due to trailing edge failures along with the calculated ratios given in Table 2.3. The resulting value is the annual cost of MR blade returns due to trailing edge failures after wedge implementation.

The annual cost of blade returns due to trailing edge failures after wedge implementation is proportional to the projected peacetime flight hours. This means that as flight hours increase, the likelihood of having a trailing edge failure on a MR blade increases as well.

2.2.1.5 Material Cost Avoidance Benefit & Projected Cash Flow

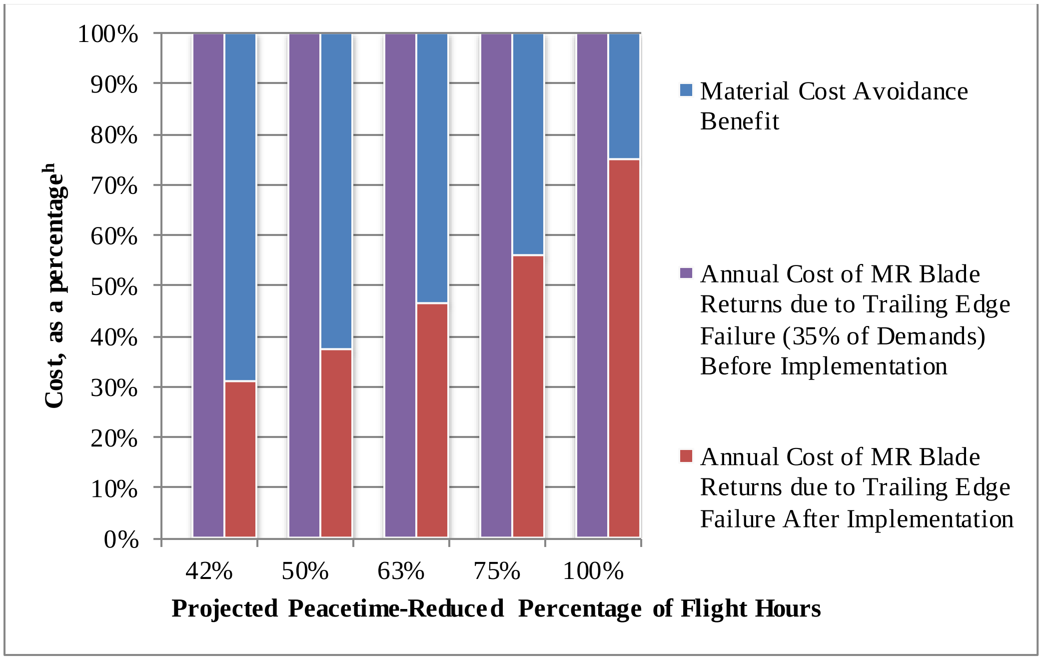

Figure 2.4: Bar Graph Displaying Material Cost Avoidance Benefit

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[h] Values taken as a percentage of the annual cost of MR blade returns due to trailing edge failures before implementation

The material cost avoidance benefit is the difference between the current cost and the new forecasted cost. The benefits decrease as flight time increases. A graphical representation of that is shown above in Figure 2.4.

The next step is to use the cost avoidance benefit to calculate the benefits achieved over a 10-year period of time. The projected cash flow over 10 years is illustrated on a graph in Figure 2.5. The lines on the graph appear to be nonlinear toward the end. This is due to the full benefit being achieved in both FY18 and FY19, so inflation is the only difference between the two.

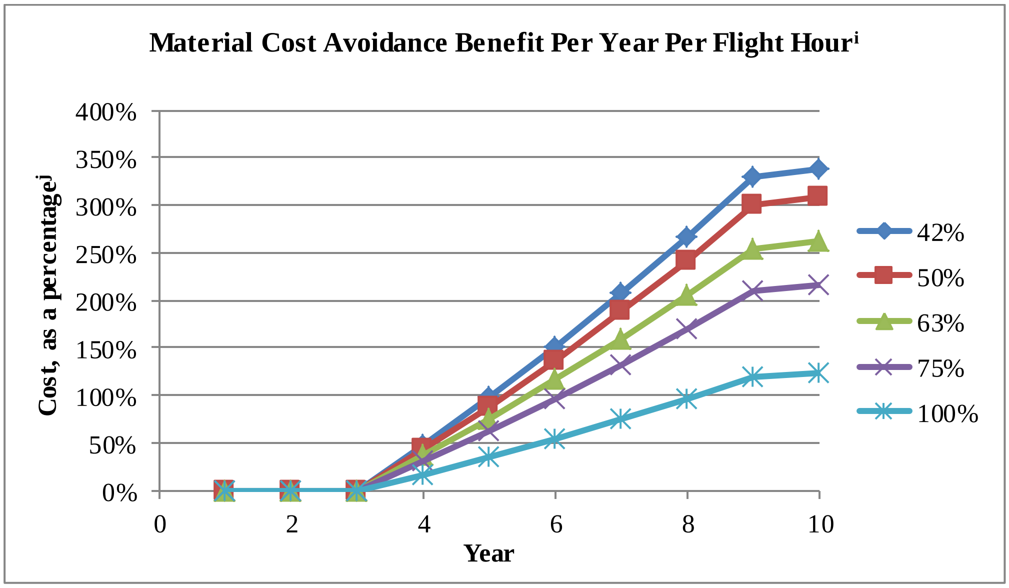

Figure 2.5: Annual Percentage of Material Cost Avoidance Benefit Achieved

Since the data collected is from FY09 through FY11, it is estimated that the benefits will not begin until two years after the last set of data acquired. This means that the benefits begin in FY13. The total benefit will not be seen in its entirety during FY13 but will be seen progressively. An incremental benefit of approximately 16.67% per year was chosen so that by FY18, a 100% benefit is achieved. These calculations also take

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[i] Projected peacetime-reduced flight hours as a percentage of current flight hours

[j] Cost per year per flight hour taken as a percentage of current rate material cost avoidance benefit

into account a 3% inflation rate, which was compounded for single flow, also beginning in FY13. The inflation equation is mathematically expressed as:

$$F = P(F/P, i\,\%, N) = P(1+i)^N$$

where P is the present single sum, F is the future single sum, i is the interest per period in percent, and N is the period (beginning in FY13) [12].

2.2.2 Operational Cost Avoidance

Operational costs are determined by using phase maintenance to determine how much it costs to perform rotor smoothing events before and after wedge implementation. Based on pilot experience, a reduction in maintenance test flight time is observed. The additional cost of wedge packets is considered here.

2.2.2.1 Rotor Smoothing Events for Fleet

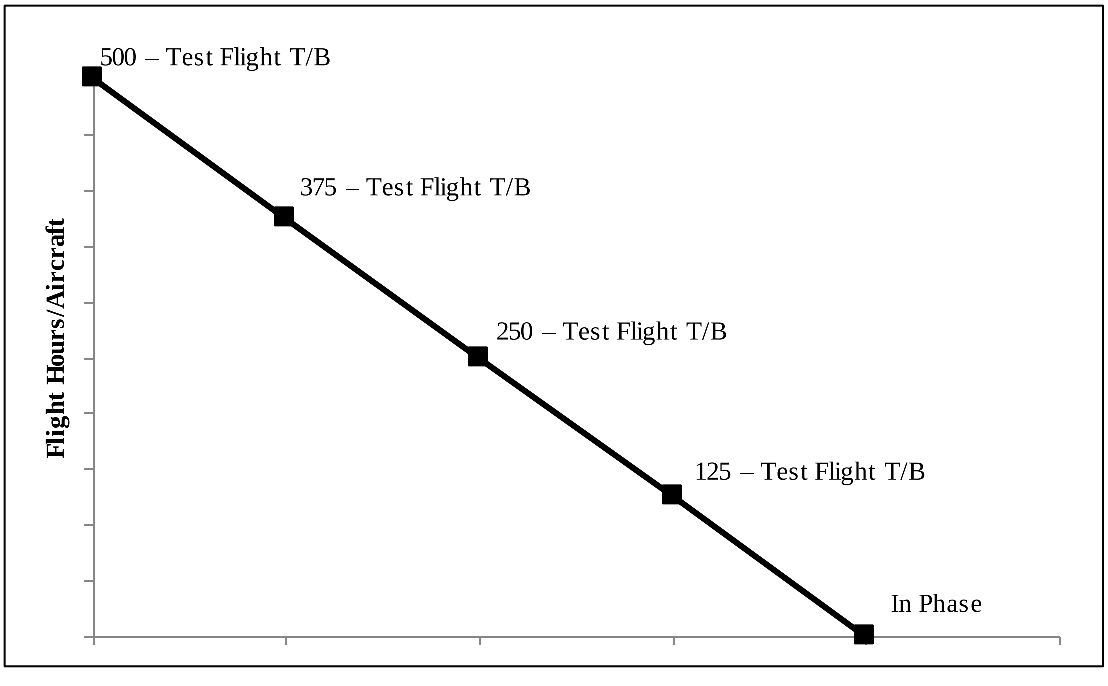

Figure 2.6: Phase Cycle for the AH-64D

It is difficult to determine the exact number of rotor smoothing events per year since they must sometimes be performed during unscheduled maintenance events. Phase maintenance is used to create a baseline allowing a comparison between the before and after costs. Phase maintenance, when related to aircraft, is a system of scheduled maintenance events. For the AH-64D, phases occur every 500 flight hours. Rotor smoothing events are guaranteed at every 125-hour interval within the phase; this is illustrated in Figure 2.6. T/B stands for "Track/Balance".

The calculations to determine the number of annual rotor smoothing events is done on an incremental inspection basis. This means that the number of rotor smoothing events per month for aircraft is determined for the 500-, 375-, 250-, and 125-flight hour incremental inspections separately. Those values are added up to determine the total number of rotor smoothing events per month for the fleet. Once that number is multiplied by 12 months/year, the annual number of RS events for the fleet is determined. The results of the calculations are proportional to the projected peacetime flight hours. This means that with higher annual flight rates, the total number of RS events will increase.

2.2.2.2 Operational Costs Prior to Wedge Implementation

Test flight patterns (TFP) are used in rotor smoothing events. A test flight pattern is a pre-determined path, or pattern, that is flown by the maintenance test pilot (MTP). In this case, TFP are performed at the beginning of a RS event and after each set of adjustments made to the blades in order to confirm those adjustments. TFP take approximately 15 minutes to complete, or 0.25 hours. On average, 3 TFP are done every RS event when tab bending is used to track and balance the main rotor blades—one initial flight and two flights to confirm adjustments. This would be about 45 minutes every RS event. The operating cost of the AH-64D is used in this calculation. This cost is unburdened, which means that it does not include maintenance man hours. Using the values mentioned above along with the annual RS events for the fleet, the annual cost of RS events for the fleet prior to wedge implementation is able to be calculated.

2.2.2.3 Operational Costs After Wedge Implementation

With the implementation of wedges, it is predicted that the number of TFP will be reduced from 3 to 2 per rotor smoothing event. This can be expected because, as it was stated previously, wedges allow for a more precise adjustment as compared to trim tabs, so less TFP are required. Additionally, during initial testing of the wedges, Boeing determined that the use of the wedges provide "a significant reduction in the number of iterations that are required to achieve acceptable airframe vibration level" [11]. Instead of 45 minutes of flight time during these events, there will now be only 30 minutes of flight time. The calculated values result in a 33% reduction in costs.

Since tab bending will no longer be used, the analysis must also take into account the cost of the wedges as an additional cost. Approximately 3 wedge packets are used during each rotor smoothing event, which is multiplied by the cost of the packet to acquire the cost of wedge packets per RS event. Instead of being replaced at every 125-flight hour interval within the phase, or four times every phase, the wedges are replaced every 250 flight hours, or twice every phase. This means that the annual rotor smoothing events for fleet value can be reduced to half of the original number when determining the annual cost of wedge packets for the fleet; the resulting values are equivalent to almost 9% of the operational costs after wedge implementation.

Although the cost of the wedge packets is a material cost, it is used in the operational cost calculations because it is dependent on the amount of rotor smoothing events per year. Adding the annual cost of rotor smoothing events after wedge implementation to the annual cost of the wedge packets for the fleet will yield the annual cost after wedge implementation.

2.2.2.4 Operational Cost Avoidance Benefit & Projected Cash Flow

The operational cost avoidance benefit is calculated the same way as the material cost avoidance benefit: the difference between the current cost and the new forecasted cost. The operational cost avoidance benefit increases as flight time increases, which is unlike the trend seen in the material cost avoidance benefit. This is because there is a 27% cost avoidance across the board. It can be compared to shopping a sale at a department store. If everything in the store is 30% off, the customer will have a greater "savings" when buying a $100 item as compared to buying a $50 item. The same concept is experienced in this situation. A graphical representation of the operational cost avoidance benefit values is shown in Figure 2.7.

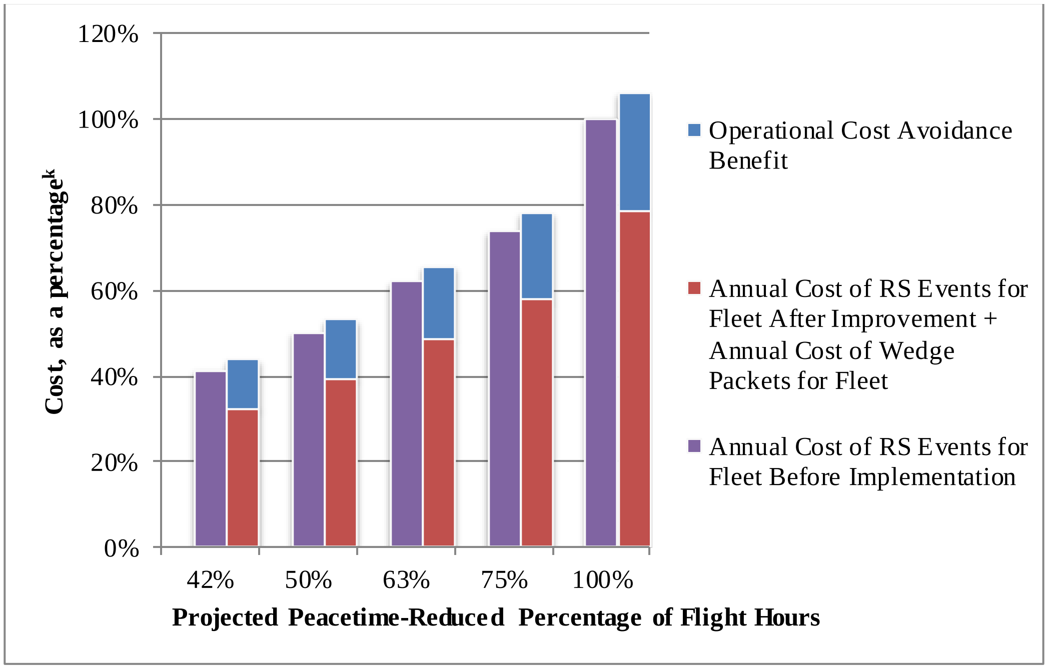

Figure 2.7: Bar Graph Displaying Operational Cost Avoidance Benefit

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[k] Values taken as a percentage of current rate annual cost of RS events for fleet before implementation

As before, the cost avoidance benefit is used to calculate the benefits achieved over a 10-year period of time. For consistency, the benefits will not begin until FY13, just as they did with the material cost avoidance benefit. The total benefit will not be seen in its entirety during FY13 but will be seen progressively. An incremental benefit of approximately 16.67% per year was chosen so that by FY18, a 100% benefit would be achieved. These calculations also take into account a 3% inflation rate, which was compounded for single flow, also beginning in FY13. The projected cash flow over 10 years is illustrated on a graph in Figure 2.8. The lines on the graph appear to be nonlinear toward the end. This is due to the full benefit being achieved in both FY18 and FY19, so inflation is the only difference between the two.

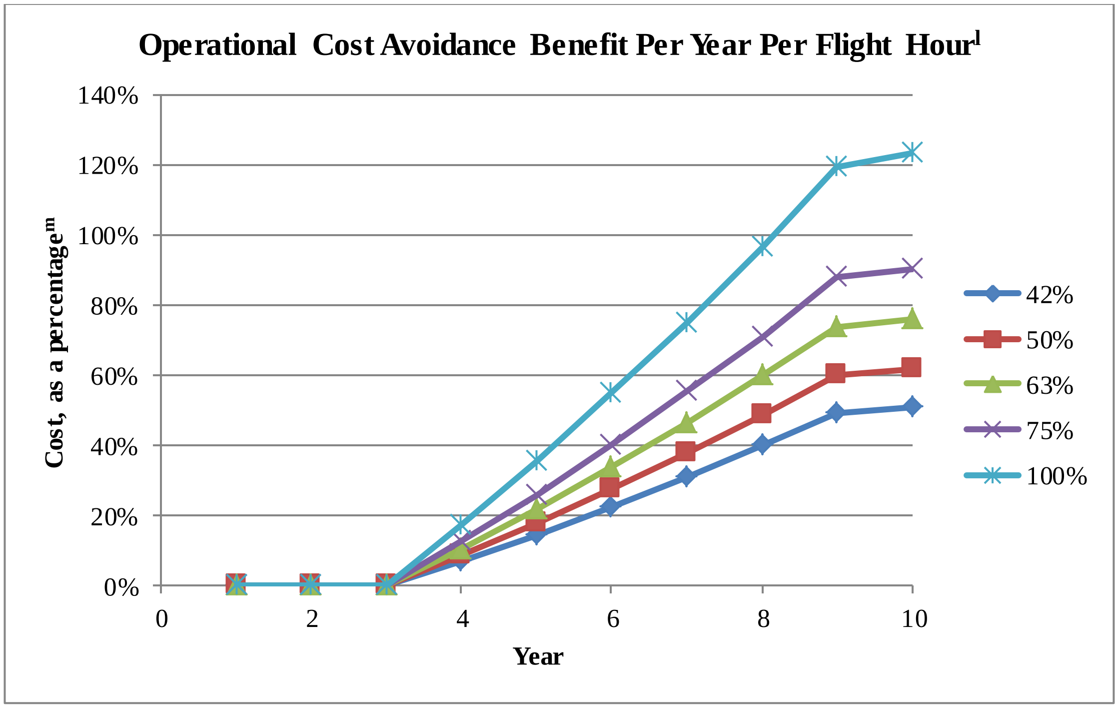

Figure 2.8: Annual Percentage of Operational Cost Avoidance Benefit Achieved

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[l] Projected peacetime-reduced flight hours as a percentage of current flight hours

[m] Cost per year per flight hour taken as a percentage of current rate operational cost avoidance benefit

2.2.3 Total Cost Avoidance Benefit

By adding the material cost avoidance benefit and the operational cost avoidance benefit, the total cost avoidance benefit is obtained. Figure 2.9 displays the total cost avoidance benefits for each projected peacetime flight hours broken down by material and operational cost avoidance benefits. The graph shows that overall the trend is that benefit decreases with increasing flight time. It also shows that the majority of the benefit comes from the costs that will no longer be spent on blade demands due to the trailing edge failures.

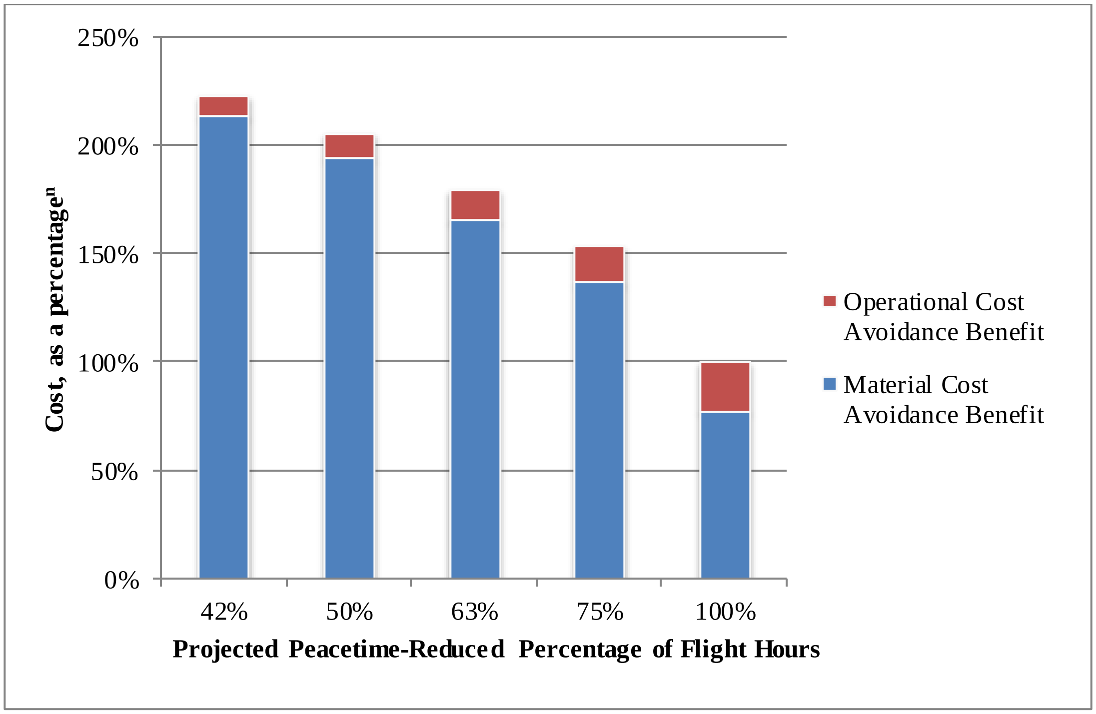

Figure 2.9: Total Cost Avoidance Benefit Graph

2.2.4 Return on Investment (ROI)

A return on investment is a way to evaluate the efficiency of an investment; the result is expressed as a percentage or ratio. In this case, it is used to predict the return, or

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[n] Values taken as a percentage of current rate total cost avoidance benefit

cost avoidance, that will be gained in the future. The formula for determining the ROI is given as such:

$$ROI = \frac{Benfit - Expense}{Expense}$$

The expense is taken as the total investment in the Vibration Control project. The first investment is given in FY10. The second investment is given in FY11 and is equivalent to 53% of the first investment. The final investment is given in FY12 and is equal to 24% of the first investment. These costs are known as sunk costs because they have already been incurred and cannot be recovered. The benefit is determined by using the total cost avoidance. Figure 2.10 illustrates how much of the ROI that is achieved per year. Table 2.4 displays the return on investment values determined for each assumed flight hour/month.

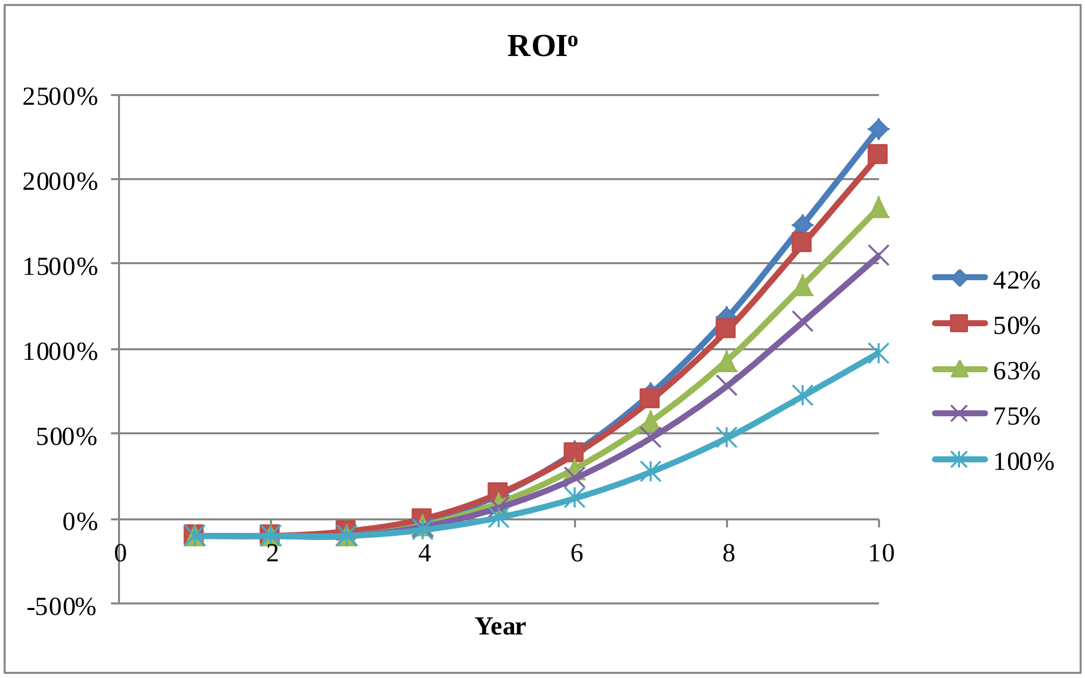

Figure 2.10: Percentage of ROI Achieved per Year using Material and Operational Cost Avoidance

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[o] Projected peacetime-reduced flight hours as a percentage of current flight hours

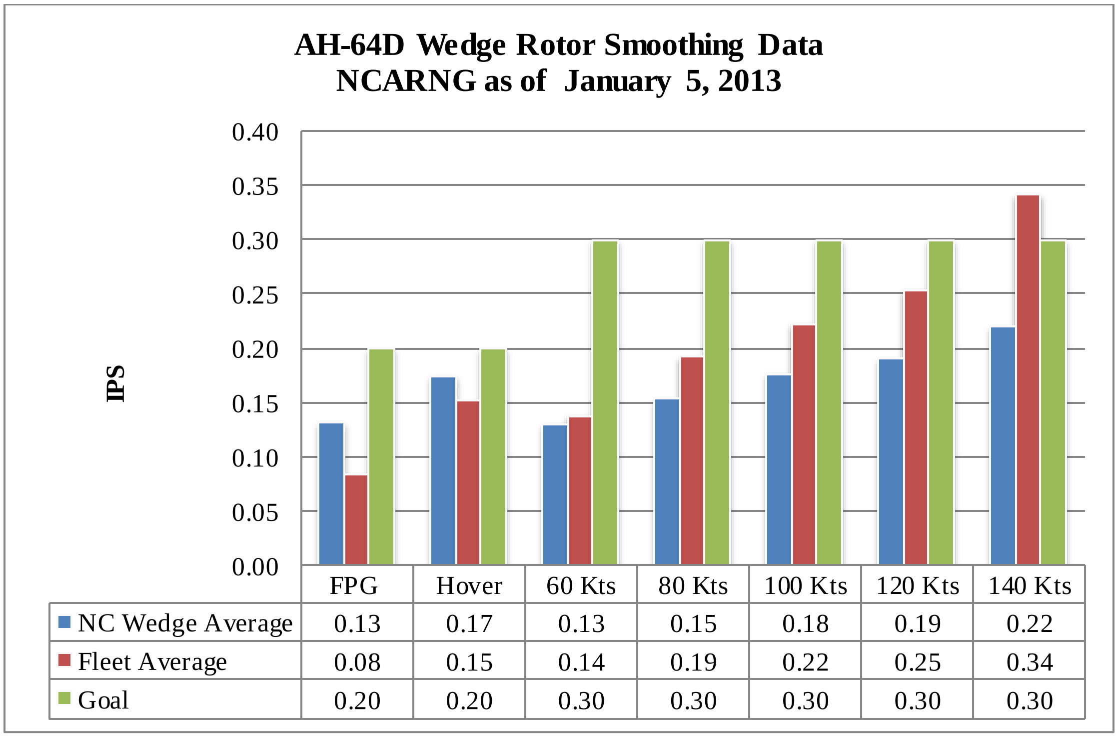
Table 2.4: Return on Investment

Projected Peacetime-Reduced Flight Hours	Return on Investment (ROI)
42%	2300.42%
50%	2114.69%
63%	1832.50%
75%	1550.31%
100%	978.09%

2.3 Additional Benefits

This analysis has demonstrated that elastomeric tracking wedges provide a substantial amount of benefits. Reducing the time spent on maintenance test flight patterns also reduces the maintenance man hours (MMH) involved in a rotor smoothing event. This value is difficult to calculate because the time spent balancing rotor blades can be vastly different between aircraft. This holds true more so for trim tab bending as compared to wedges. Discussion with maintenance crew members revealed that the length of rotor smoothing events using the tab bending tool can range from a couple of hours to a full work day. This suggests that rotor smoothing events without wedges are a huge strain on MMH and hinder the availability of the aircraft.

Figure 2.11 is a chart comparing rotor smoothing vibration levels from North Carolina Army National Guard (NCARNG) and the AH-64D fleet against the Army’s goal. The NCARNG fleet uses only wedges for rotor smoothing and the rest of the Army's fleet uses tab bending for rotor smoothing. The data collected is from January 2012 through January 2013. FPG stands for “flight pitch ground” which means there is no pitch in the blades while on the ground. The vibration is measured in inches per second (IPS). The first thing to recognize about the chart is that all wedge levels are below the goal. At FPG and Hover, the wedge vibration average is higher than the fleet average. This is not significant because the majority of flight time is spent from 60 KTS to 100 KTS, where the wedge average is lower than the fleet average. Overall, it is safe to say that the use of wedges results in lower vibration levels as compared to vibration levels experienced by aircraft using tab bending.



	FPG	Hover	60 Kts	80 Kts	100 Kts	120 Kts	140 Kts
🟦 NC Wedge Average	0.13	0.17	0.13	0.15	0.18	0.19	0.22
🟥 Fleet Average	0.08	0.15	0.14	0.19	0.22	0.25	0.34
🟩 Goal	0.20	0.20	0.30	0.30	0.30	0.30	0.30

Figure 2.11: NCARNG AH-64D Wedge Rotor Smoothing Data, provided by Stanley H. Graves

According to the AWR for the MSPU [13], "rotor smoothing adjustments recommended by the MSPU system…may be made without necessitating an additional maintenance test flight. Relief from the maintenance test flight requirement only applies if MSPU measured vibration levels are 0.50 IPS or less and the displayed Main Rotor Smoothing status is green or green with an upward arrow." When looking at the figure above, it can be seen that all of the vibration levels from wedge aircraft are far below 0.50 IPS. This means that the number of maintenance test flights can be further reduced with the use of elastomeric wedges instead of bending tabs.

2.3.1 Examples of Second Order Effects from Lower Vibration Levels

Lower vibration levels can result in a multitude of second order effects. The results/benefits found in the following examples can be applied to the vibration effects expected from the AH-64D.

2.3.1.1 Rotor Mounted Bifilar Vibration Absorber Study (1970)

Angelo C. Veca [14] wrote about the vibration effects on helicopter subsystem reliability, maintainability, and life-cycle costs. The study examines two groups of United States Air Force (USAF) H-3 helicopters: one equipped with a rotor-mounted bifilar vibration absorber and one without the absorber. The aircraft were alike in all other respects. Each group consisted of 15 aircraft each and conducted approximately the same number of flight hours during the time period covered by the study [14]. The bifilar vibration absorber reduces helicopter vibration induced by the rotor. The evidence in this report indicates that a decreasing vibratory stress level from the absorber results in a decreasing failure rate as well as a significant reduction in direct maintenance. With an average vibration level reduction of 54.3%, "the overall H-3 helicopter failure rate and corrective maintenance are reduced by 48% and 38.5%, respectively. Correspondingly, life-cycle costs show a significant reduction of approximately 10% for the overall aircraft." It goes on to state, "The improved reliability resulting from the reduced vibratory stress environment results in less corrective maintenance being expended on the H-3 aircraft. This results in less downtime on the aircraft, thereby improving availability and contributing to the reduction in the operating cost of the aircraft." Additionally, the paper concludes that "the reductions are manifested by lessening the costs of direct maintenance manpower and spares, and by improving helicopter utilization." Figure 2.12 is a chart from the report displaying a comparison of the total average failure rate and maintenance man-hours per 1000 flight hours (MMH/KFH) for the top 13 aircraft subsystems. It highlights the “dramatic reduction in both average failure rate and maintenance man-hours that appears to result from the reduction in vibration.”

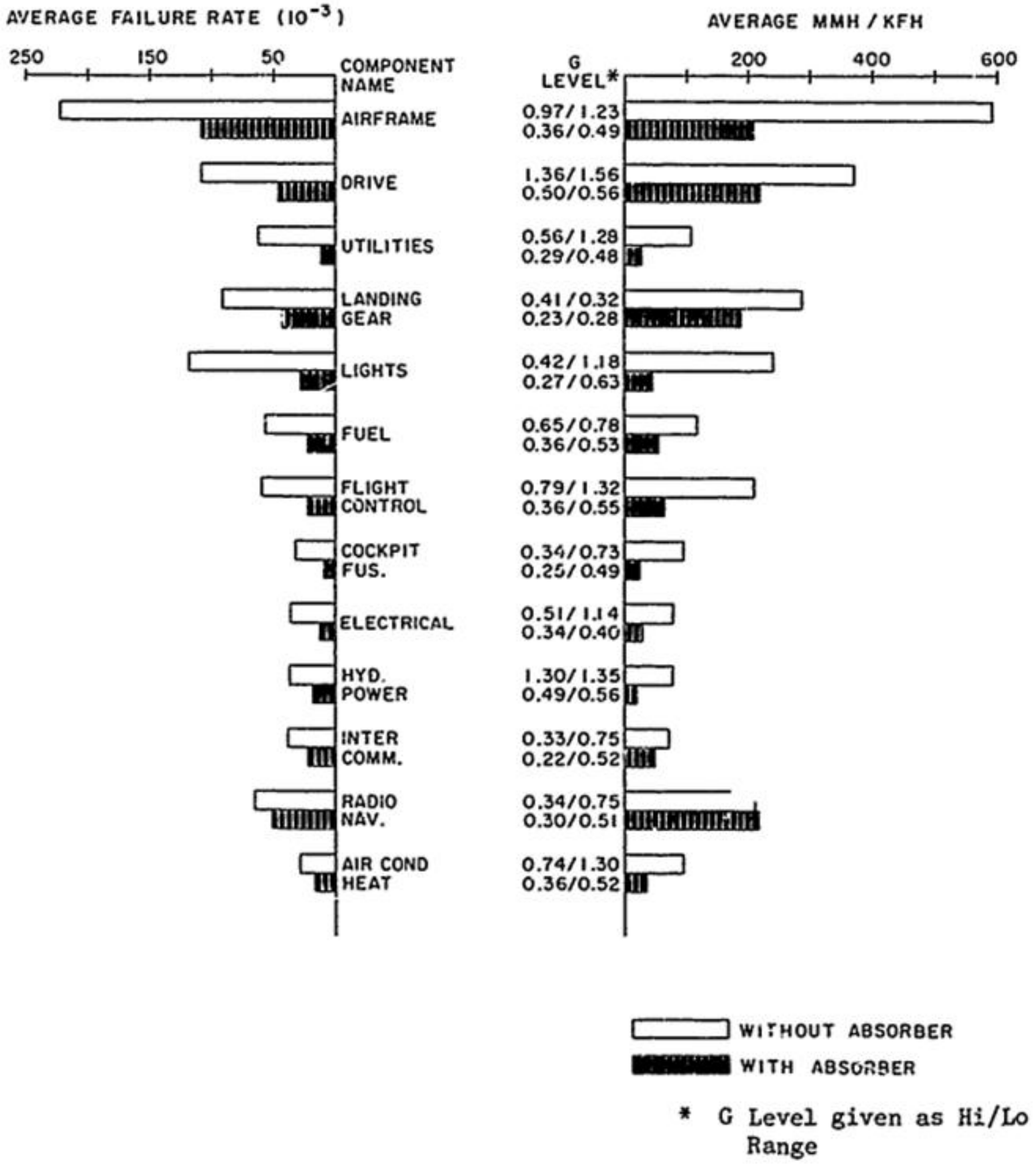


Figure 2.12: Comparison of Total Average Failure Rate & MMH/KFH for Top 13 Aircraft Subsystems [14]

2.3.1.2 UH-60 Vibration Surveys (1988)

Vibration surveys on the UH-60 aircraft were conducted in 1988 by U.S. Army Aviation and Surface Material Command's (AVSCOM, which is AMCOM today) Aeromechanics. A sample of 9 aircraft from Fort Rucker and 12 aircraft at Fort Campbell were surveyed. The results showed that the vibration levels for the aircraft at Fort Campbell were twice that of Fort Rucker's and are given in Table 2.5. Additionally, unscheduled maintenance removal and replacement rates were studied. This study found that Fort Rucker maintained UH-60 aircraft had one-half the removal and replacement rates of regular Army UH-60 aircraft [15]. The equipment categories that were surveyed are the following: instruments, avionics, flight controls, and electrical systems.

Table 2.5: UH-60 1P/4P Survey & Removal and Replacement Rate Results [15]

	Average Vibration Levels at 140 Kts		Unscheduled Maintenance Removal & Replacement Rates
	1P	4P	
Fort Rucker (Sample of 9 aircraft)	0.2 IPS	0.3 IPS	23 per 1000 flight hours
Fort Campbell (Sample of 12 aircraft)	0.4 IPS	0.55 IPS	51 per 1000 flight hours

2.3.1.3 Navy P-3 Orion Propeller Dynamic Balancing

Although vibration in a fixed wing aircraft is inherently less severe than in rotary wing aircraft, reducing the aircraft's vibration level is still critical to the longevity of its components [16]. In the early 80s, the propellers of 200 P-3 aircraft were dynamically balanced. Prior to balancing, the average vibration was 0.40 IPS. After balancing, the average vibration level dropped to 0.15 IPS. For six months prior to and six months following the propeller balancing, the Navy tracked the maintenance records of the 200 aircraft for nine selected systems. The Mean Flight Hours Between Failure (MFHBF) for the aircraft with balanced propellers doubled that of the unbalanced propellers. The results can be seen in Figure 2.13 [17]. Lower vibration levels lead to an increase in MFHBF for every single system that was monitored, with MFHBF increases ranging from approximately 90 to 180 hours.

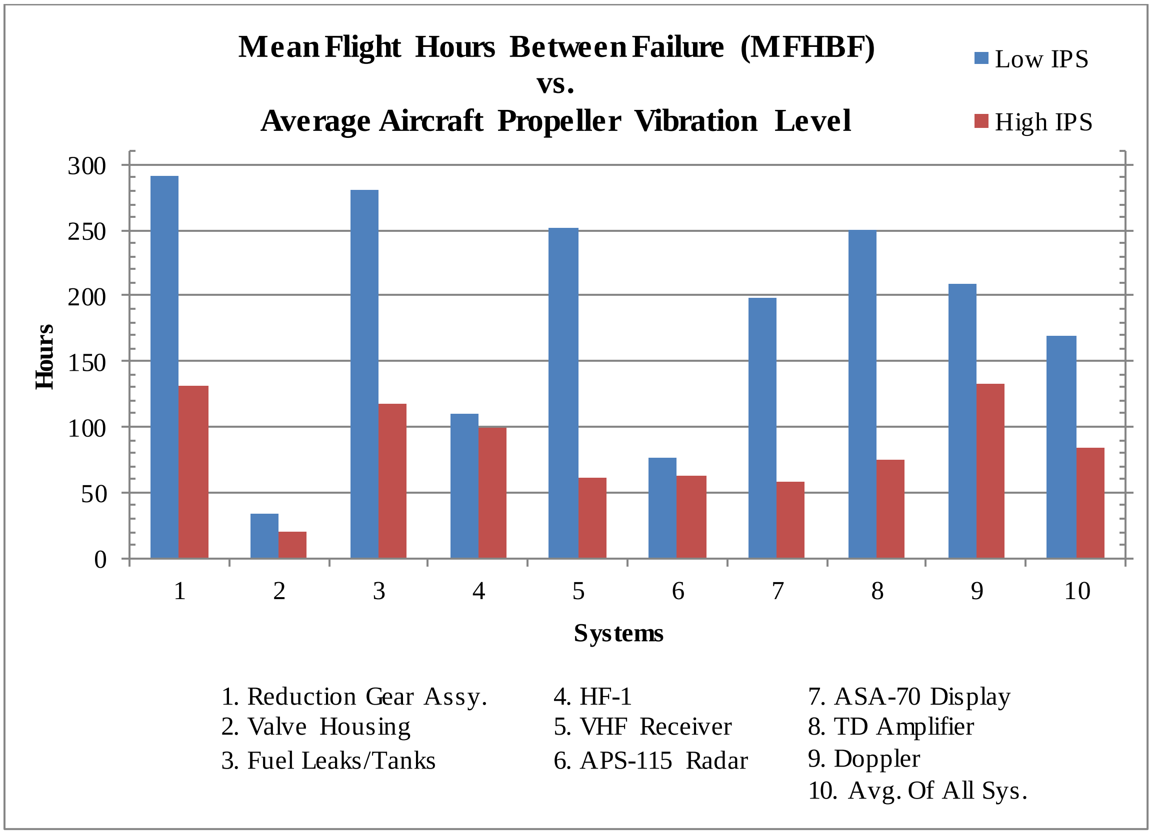


Figure 2.13: Mean Flight Hours Between Failure (MFHBF) vs. Average Aircraft Propeller Vibration Level [17]

The findings from the study shown above prompted a follow-up study. In the second study, data was collected from 1,797 dynamically balanced propellers, before and after the balance. The mean vibration level had decreased from 0.252 IPS to 0.05 IPS and the standard deviation decreased from 0.158 IPS to 0.042 IPS. Over two years, Nava; Air Test Center (NATC) followed 15 aircraft and found that the lower vibration levels led to a reduction of 11.5% in the MMH per flight hour. Following the second study, it was decided to implement dynamic balancing procedures [18].

A third study was done to determine the optimum vibration level of the propeller and the effects of spinner replacement on the propeller's vibration level. One hypothesis from this study is that aircraft with propellers dynamically balanced to ≤ 0.10 IPS would require fewer maintenance man hours per flight hour than aircraft with propellers balanced to ≤ 0.20 IPS. A squadron of eight aircraft was split into two groups with four aircraft each—the treatment group and control group. The first group was balanced to ≤ 0.10 IPS and the second group was balanced to ≤ 0.20 IPS. The results are shown in Figure 2.14.

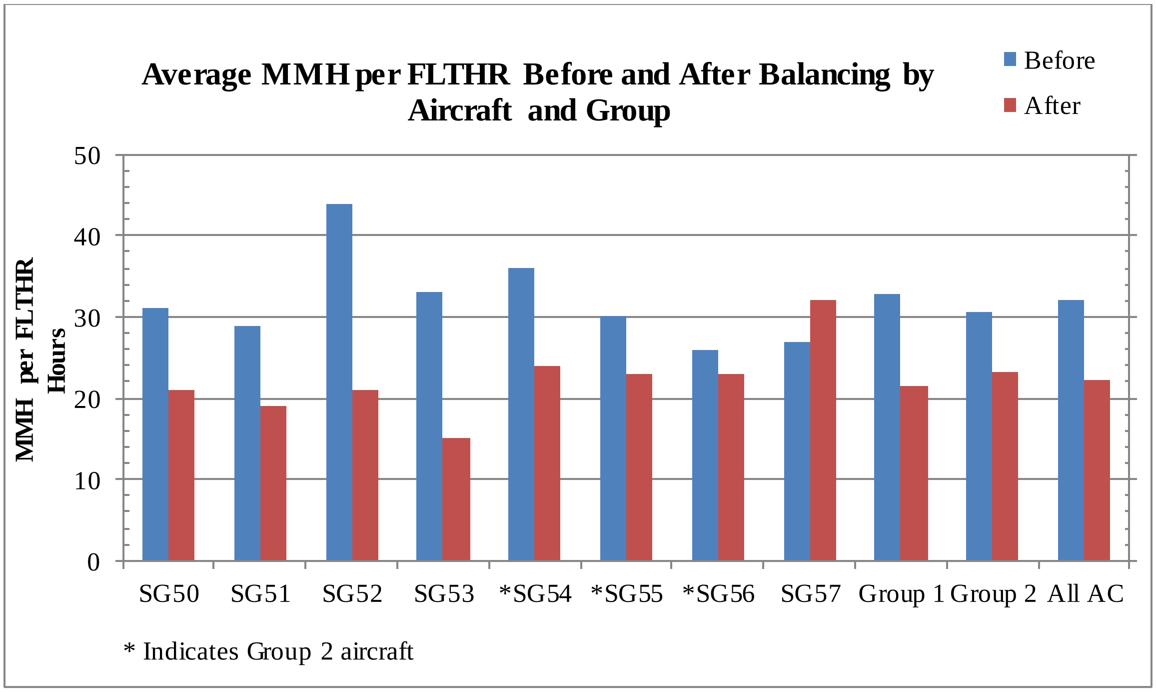


Figure 2.14: Average MMH per FLTHR Before and After Balancing by Aircraft and Group [16]

The results shown above support the hypothesis that propellers with lower vibration levels require fewer maintenance man hours per flight hour. It was concluded that the preferred vibration level is ≤ 0.10 IPS for the following reasons: 1) it will prevent the propeller's vibration level from exceeding the maximum acceptable level of 0.20 IPS; 2) it reduces the cost of operations by increasing equipment mean flight hours between failure and reducing the amount of maintenance; 3) little or no additional maintenance cost was incurred when dynamically balancing the propeller to ≤ 0.10 IPS instead of ≤ 0.20 IPS [16].

2.4 Future Work

The AH-64 self-adhering wedges have been modified to fit the H-47 and H-60M aircraft. Initial testing has been completed for both helicopters leading to a limited AWR being released for the H-47 and one being expected for the H-60M. Reports from the test locations indicate that intermediate unscheduled RS events are almost never needed as the wedges maintain rotor system vibrations at maintenance test flight levels between maintenance intervals [6]. Users from multiple locations state that wedges are preferred over the use of trim tabs. These reactions suggest that the use of elastomeric wedges should be investigated for additional aircraft and would lead to desirable vibration levels.

Wedge equipped and non-wedge equipped aircraft vibration levels will continue to be monitored. Along with the vibration levels, fuel consumption can be tracked to see what relations may exist between the two. Reduced vibration will lead to fewer structural-fatigue-related faults which can be discovered by observing internal mechanical and electrical components. An increase in mean time between failure and a reduction in removal and replacement rates is expected as well. The MR blades can be tracked to observe extended component life and likewise, a reduction in demand. MR trailing edge failures can be monitored to see just how many exist after the introduction of wedges to maintenance protocol.

2.5 Summary

It is safe to say that elastomeric wedges used on AH-64D main rotor blades are an improvement in rotor smoothing events over bending the trailing edge metal trim tabs. Wedges are quicker, easier, and more accurate than bending tabs, for installation and use over time. This means that maintenance delay due to limited tooling or an absence of trained maintainers will be eliminated. The wedges provide the same change in lift and pitching moment characteristics as tab bending. Trim tab washout is not an issue with wedges since the metal tab is no longer being bent to hold an angle.

Due to the tracking accuracy of the wedges, the maintenance test flight patterns flown during rotor smoothing events decrease by, on average, one test flight pattern per event, which results in a 33% reduction in operational test flight pattern hours during phase maintenance across the entire fleet. The elastomer that the wedges are made from have a high resistance to chemical and environmental exposure, which means that wedges only need to be applied every 250-flight hours within the phase instead of every 125-flight hours. Even with the addition of wedges as a cost, a 27% reduction in operational costs before wedge implementation exists. This value increases as flight time increases.

It has been demonstrated that the use of tracking wedges will decrease the overall MR blade demand by reducing the amount of trailing edge failures experienced by main rotor blades. The material cost avoidance increases as flight time decreases. The majority of the total cost avoidance benefit comes from the blades that will no longer be returned and demanded due to trailing edge failures.

The use of elastomeric wedges result in lower levels of vibration which leads to the following benefits: less corrective maintenance actions (and thus, MMH required), reduced downtime, lowered component failure rate, a reduction in removal and replacement rates, increased mean time between failure, increased reliability, increased availability, and increased maintainability. Three out of four Condition Based Maintenance (CBM) objectives are affected: the soldier and maintenance burden is reduced, operational support cost is reduced, and aircraft availability is increased.

The analysis of both the material and operational benefits that are achieved from the use of elastomeric wedges as a form of vibration control result in a 10-year return on investment of between 9.8:1 and 23:1 for the current rate of flight and a range of projected peacetime flight hours.

CHAPTER 3. CASE STUDY II

3.1 Background

The U.S. government spends hundreds of billions of dollars annually on its defense budget. Over the past few years, the budget has gradually been reduced. With these budget cuts, the military must develop new methods of cost avoidance. According to the Aviation and Missile Command's (AMCOM) integrated priority list, the turboshaft engine is the number one cost burden to the Army with Army Working Capital Fund (AWCF) sales[p] exceeding $260M for FY13 and projected sales[q] over $200M for FY14. Many cost-saving initiatives have been proposed and implemented to optimize operations and support (O&S) efforts [19]. One effective way to avoid costs is to focus on maintenance. By increasing the life of components and by streamlining maintenance processes, the frequency of maintenance events is reduced and costs can be avoided.

3.1.1 Maintenance Levels

The Aviation Maintenance concept for Army aviation defines three maintenance levels: Aviation Unit Maintenance (AVUM), Aviation Intermediate Maintenance (AVIM), and Depot Maintenance. The condensed descriptions of each maintenance level follow.

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[p] Total AWCF Sales (last 12 months) is defined as "Dollar value of the AWCF sales for the last 12 months calculated by multiplying the AMDF price times the number of independent demands". The AMDF Price definition states "Also known as the standard price, it includes the latest acquisition cost plus the authorized cost recovery rate (surcharge)". Independent Demands are "the demands generated by a funded requisition from a retail unit".

[q] Projected AWCF Sales (next 12 months) is defined as "Dollar value of the AWCF sales for the next 12 months calculated by multiplying the AMDF price times the number of forecasted independent demands for the next 12 months".

The lowest level activities, AVUM, are "staffed and equipped to perform high-frequency 'On-Aircraft' maintenance tasks required to maintain a level of aircraft readiness" [20]. These activities will be governed by the Maintenance Allocation Chart (MAC) and include basic/minor troubleshooting, replacements, repairs, and other tasks that do not require extensive or complex adjustments.

As stated by the Interactive Electronic Technical Manual (IETM), AVIM "provides mobile responsive 'One-Stop' maintenance support." AVIM performs all maintenance tasks that are authorized to be done at the AVUM level. AVIM can also repair selected items for return to stock and can determine the serviceability of certain modules before its expired TBO. All unserviceable repairable modules/components and end items beyond the capability of AVIM to repair will be evacuated to the third maintenance level—Depot Maintenance

Depot-level maintenance performs all maintenance tasks that are authorized to be done at the lower levels as well as "material maintenance or repair requiring the overhaul, upgrading, or rebuilding of parts, assemblies, or subassemblies, and the testing and reclamation of equipment as necessary" [21]. For all of the GE T700 turboshaft engines, which include the T700, T701, T701C, and T701D variations, there is only one depot location for returns.

3.1.2 Maintenance Process

When it is discovered that a repair or replacement must be made to the engine, the maintainer utilizes the technical manual. This allows the maintainer to run through troubleshooting procedures to evaluate the cause of the issue and remediate that issue. If the repair cannot be performed at the AVIM level, the engine is sent to Corpus Christi Army Depot (CCAD) in Texas, the only depot location for T700 engine returns. Upon its arrival at CCAD, a tear down analysis is performed on the engine and an inspector determines if the engine was field repairable (FR). This and many other details related to each engine are entered into a system called RIMFIRE, which stands for Remediation/Reliability Improvement through Failure Identification and Reporting. According to Stephanie Burke, a reliability engineer for RIMFIRE, QuantiTech, Inc., the definition for FR is "the failure mode or condition that caused the inducted item to be returned to the depot was determined to be repairable in the field, based on current unit level maintenance procedures and manuals." Additionally, the depot-level maintainer must perform the necessary repairs to the engine so that it can be put back in use.

3.1.3 Engine-Based Replacements vs. Module-Based Replacements

The engines determined to be FR after depot-level inspection can also be referred to as engine-based replacements (EBR). EBR occur when an entire engine is returned to depot to maintain fleet availability. This could be due to the inability to discover the root of the problem. Another reason is that the maintenance action requires module replacement but a spare is not in stock. In this particular case, the engine would be sent back to depot and would be replaced with an engine that is in stock. The problem with this method is that it becomes costly to send an entire engine back when only one module needs repair. Once at depot, the engine is torn down only to discover that every other module is in working condition.

The engine, shown in Figure 3.1, consists of four major modules: Accessory Section Module (ASM), Cold Section Module (CSM), Hot Section Module, and Power Turbine Module (PTM). When something fails within the modules, limited repairs can be performed by AVIM-level maintainers, and even less by AVUM-level maintainers. The alternative to EBR is module-based replacements (MBR). This means that when a particular module needs a repair done at the depot level, only the module is returned instead of the entire engine. As it is shown later, just below half of the engines that are sent to depot are determined FR solely because a module replacement would have solved the issue. MBR are sometimes frowned upon because many units tend to not have the modules in stock that need replacing. This can be seen as a burden because the module would need to be shipped to the unit before the engine could be repaired, thus lowering the aircraft readiness. By adopting the MBR system, the unit would keep new modules in stock instead of engines. This allows for a reduction in the number of engines sent to CCAD and would, in turn, reduce the cost burden the engines have on Army Aviation.

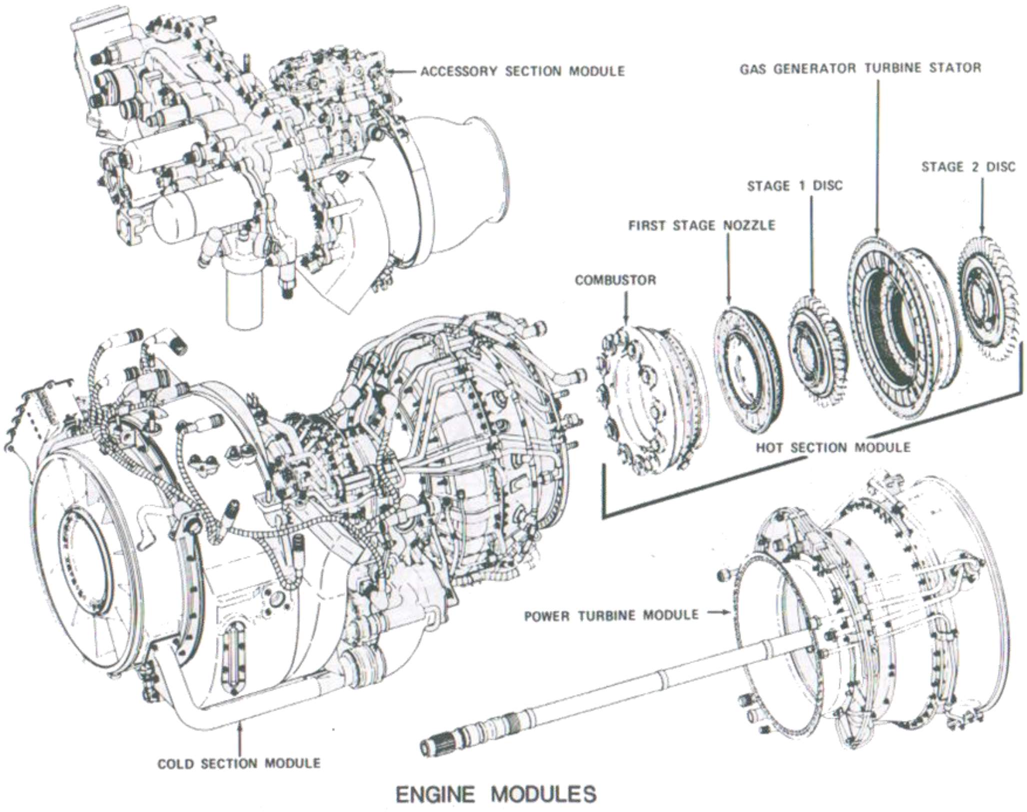

Figure 3.1: GE T700 Engine Modules [20]

3.2 Analysis

Material and operational costs are examined to ultimately determine the benefits achieved with the implementation of the proposed maintenance changes. The projected annual savings, or benefits, determined in the following analyses are taken as a cost avoidance in that these are costs that will not be spent on maintenance, but on training or missions. The material cost avoidance explores the costs associated with switching from engine-based replacements to module-based replacements as well as taking the time to make certain repairs to the engine in lieu of returning the entire engine. The operational cost avoidance considers the maintenance man hours (MMH) involved.

3.2.1 Material Cost Avoidance

Material costs are developed from RIMFIRE, the AMCOM Integrated Priority List for FY12, and Federal Logistics Data (FEDLOG).

3.2.1.1 Engine Demands for FY12

The analysis begins by acquiring the total annual demand for GE T700 series engines from the FY12 AMCOM Integrated Priority List. This list ranks each component on its cost burden to the Army. The engines used in this analysis were the only ones with a demand (independent or dependent) in FY12. Table 3.1 displays each engine with its rank and its annual demand as a percentage of the entire annual demand.

Table 3.1: Annual T700 Engine Demands for FY12 in AMCOM Integrated Priority List

Current Rank	Nomenclature	% of Total Engines
1	Engine A	57.41%
3	Engine B	18.84%
9	Engine C	13.31%
25	Engine D	7.41%
43	Engine E	3.01%

3.2.1.2 Percentage of Field Repairable Engines

A dataset was taken from RIMFIRE and includes engines dating from 07 Feb 1990 through 13 Nov 2013. As described previously, when each engine is sent to CCAD, an inspector performs a tear down analysis on the engine. This includes assessing the damage and determining whether or not the engine should have been sent to depot or if it should have been repaired in the field. The engine inspector had the option of marking the "FR" field "Y" for yes, "N" for no, "N/A" for not applicable, or it could be left blank. "Y" means that the engine could have been repaired in the field and did not need to be sent to depot for repair. "N" means that the engine could not have been repaired in the field and the maintainer was correct in sending the engine to depot for repair. "N/A" is used when the removal was due to a recap/reset or another directed removal; these types of removals rarely have a failure or a defect. Because of this definition, "N/A" engines are considered as not repairable in the field for this analysis and are added in with the "N" engines.

The ratio of "N" to "Y" engines is applied to the engines with a blank "FR" field and those engine numbers are added to the "N" and "Y" totals respectively, yielding a total percentage of FR engines to be 13.91%. It should be noted that the values for FY13 and beyond are incomplete due to the delay in RIMFIRE data entry. The fiscal year for 2013 extends from 1 Oct 2012 through 20 Sep 2013; this FY designation will be used respective to each year.

Figure 3.2 is a graphical representation of the engines that are determined to be FR by the inspector at CCAD. It is important to determine the percentage of FR engines of the annual engine demand because it is the value that will decrease with the implementation of the proposed changes and it is what the material costs focus on.

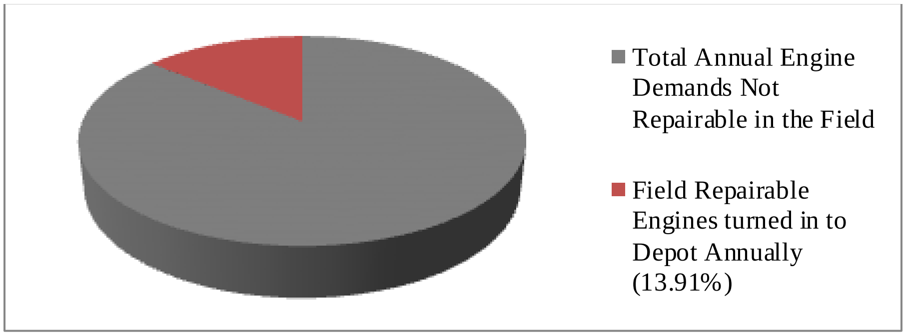

Figure 3.2: Pie Chart of Annual Engine Demands and FR Engines Returned to Depot

3.2.1.3 Field Repairable Engine Categories

Along with determining whether an engine is FR or not, the inspector also types up his or her comments and suggestions for every engine. Each of these comments was read and every FR engine was categorized by the inspector's assessment. The categories as well as their respective percentages (out of the 13.91%) are displayed below in Table 3.2. The bolded categories are the ones that could be quantified by a predetermined repair or solution given in the MAC; the unbolded categories will be discussed in a later section.

Table 3.2: Field Repairable Categories

Airfoils	**23.88%**
Clogged Cooling Holes (CCH)	**0.59%**
Compressor Stall	3.85%
Exit Rub Combination (ERC)	**1.63%**
Inserts, Studs, Bolts	4.59%
Leak	2.37%
Other	5.63%
Replacement	3.26%
Replacement – Accessory Section Module (ASM)	**2.81%**
Replacement – Combination	4.59%
Replacement – Cold Section Module (CSM)	**36.94%**
Replacement – Gas Generator (GG) Matched Assembly	**2.37%**
Replacement – Power Turbine Module (PTM)	**7.41%**

The “Airfoils”, “Clogged Cooling Holes”, and “Exit Rub Combination” categories refer to engines where the only cost associated with their repair is tied to MMH. The solution for clogged cooling holes is simply to clean out the holes. It is a fairly simple procedure. “Airfoils” refer to foreign object damage (FOD) or erosion to the compressor blades within the CSM. This type of repair is time extensive, but it leads to component life extension. This type of repair is resolved by trimming and blending the airfoils. Engines categorized by “Exit Rub Combination” are those with impeller/shroud exit rub and FOD/erosion to the compressor blades. In addition to the airfoil repair, these engines must also have the exit rub blended.

The remaining bolded categories (Replacement – ASM, CSM, GG Matched Assembly, PTM) are the module-based replacements. This means that the engine was determined FR because only the module should have been returned. For these categories, the analysis does not look at the repairs that can be done to each module upon its arrival to depot because it assumes that all remaining repairs can only be performed by depot-level maintainers, hence why it was returned to depot. The GG Matched Assembly is part of the Hot Section Module and is one of the few repairs that can be made by AVIM-level maintainers to the interior of the modules.

3.2.1.4 Material Costs Before: Engine-Based Replacements (EBR)

The annual engine demand for FY12 was multiplied by the 13.91% of the engine demand that were determined to be FR. This yielded the actual number of engines that would be affected on a yearly basis by improvements to the maintenance process to decrease the number of FR engines. This number is then multiplied by the percentage of a single field repairable category, as given in Table 3.2. Since each repair from Table 3.2

requires a different cost analysis, a material cost is determined separately for each category. For example, if the “Clogged Cooling Holes” category is being examined, the way to discover the number of engines determined FR by repairing CCH is the annual engine demand for FY12 multiplied by the 13.91% of the engine demand that were determined to be FR multiplied by 0.59%, which is the percentage of FR engines categorized as CCH. This equation will be how the base engine number (number of engines affected) is calculated for each FR category; it will also be used in the following section.

Now that the number of engines affected can be determined, the cost must be applied. FEDLOG was used to obtain the Army Unit Price (AUP) and the Serviceable Credit Value (SCV) of the engine. The AUP is the standard price of the unit and the SCV is the credit amount for the turn-in of a serviceable item. Using the demands for engines A-E, a weighted average value was determined for the AUP and SCV. The weighted average simplifies the analysis by creating a single AUP and SCV for the engine and it weights each engine’s cost relative to its annual demand. The difference between AUP and SCV is the sunk cost, or money lost, every time a serviceable engine is returned to depot.

Figure 3.3 shows the money lost for each EBR taken as a percentage of the weighted average money lost for EBR. The thick black line designates where the weighted average money lost for EBR is relative to the individual engines. It can be seen that Engine C and Engine E are the largest sources for money lost for EBR.

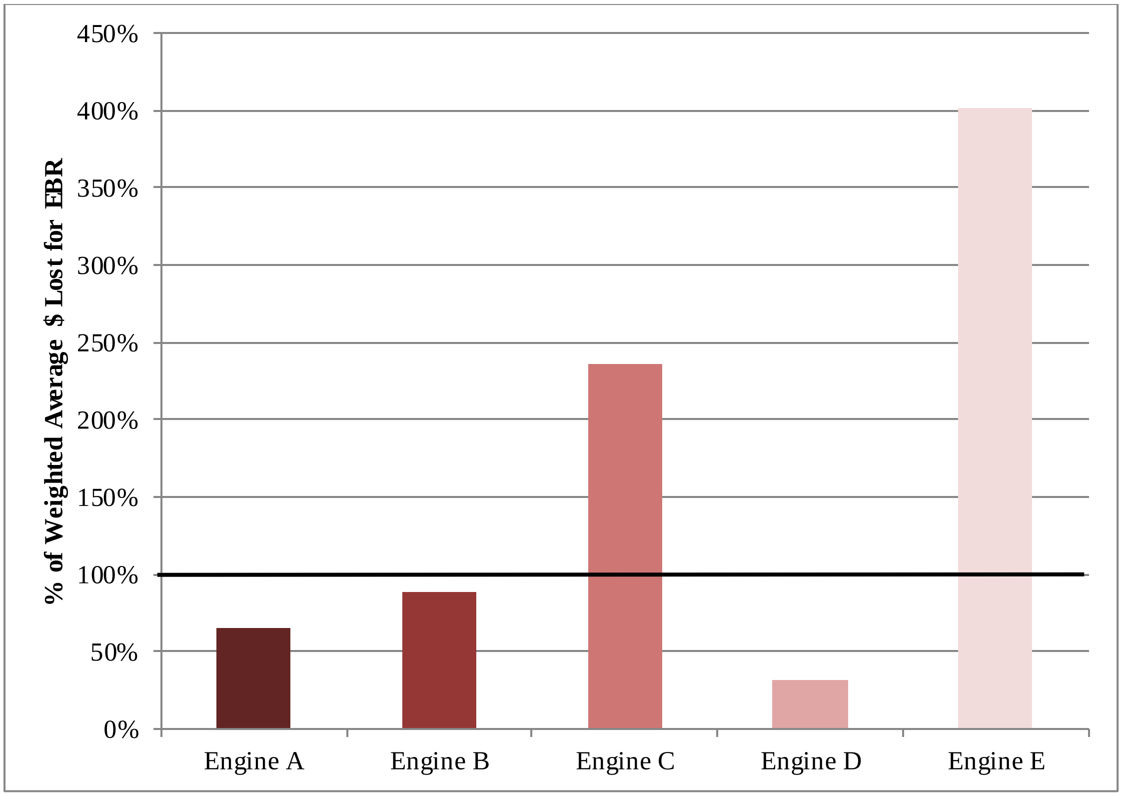

Figure 3.3: Money Lost for Each EBR as a Percentage of Weighted Average EBR

3.2.1.5 Material Costs After: Module-Based Replacements (MBR)

The only FR categories with material costs associated with them are the MBR. Looking back at Table 3.2, it can be seen that almost 50% of the FR engines are due to MBR. This is significant because by switching to MBR from EBR, over half of the FR engines will no longer be sent to depot unnecessarily.

The total number of each module demanded annually was taken from the AMCOM Integrated Priority List. This list ranks each component on its cost burden to the Army. The modules used in this analysis were the only ones with a demand in FY12. Similar to the engine demand, these demand values will be used to calculate weighted average costs for each module. Table 3.3 displays each module with its rank and its annual demand as a percentage of the entire annual demand per module.

Table 3.3: Annual T700 Module Demands for FY12 in AMCOM Integrated Priority List

Current Rank	Nomenclature	% of Total Module
185	ASM A	87.23%
933	ASM B	12.76%
4	CSM A	86.10%
53	CSM B	13.89%
11	GG A	69.73%
173	GG B	9.86%
281	GG C	2.24%
542	GG D	9.64%
2274	GG E	8.52%
13	PTM A	78.41%
89	PTM B	21.58%

FEDLOG was used to acquire the costs involved with the modules. The AUP and SCV were obtained for each module as well as a third cost: Unserviceable Credit Value (UCV). The UCV is the credit amount for the turn-in of an unserviceable item. Using the demands for the separate modules, a weighted average value was determined for the AUP, SCV, and UCV. Again, the weighted average simplifies the analysis by creating a single AUP, SCV, and UCV for the modules and it weights each individual module's cost relative to its annual demand as part of its respective module. The difference between AUP and SCV here is the money lost every time a serviceable module is returned to depot. Similarly, the difference between AUP and UCV is the money lost every time an unserviceable module is returned to depot. Graphs displaying the difference in money lost between SCV and UCV for each module are given below in Figures 3.4-7. These graphs highlight the large difference between the two values for each module.

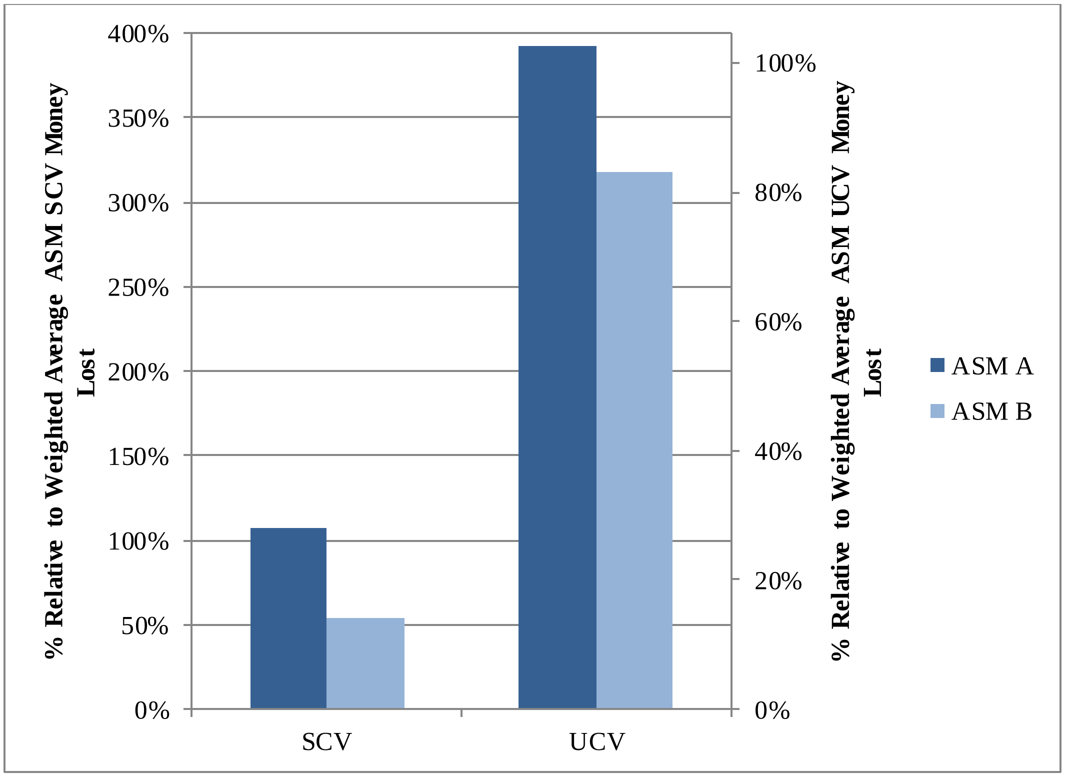

Figure 3.4: ASM SCV and UCV Money Lost Relative to Another

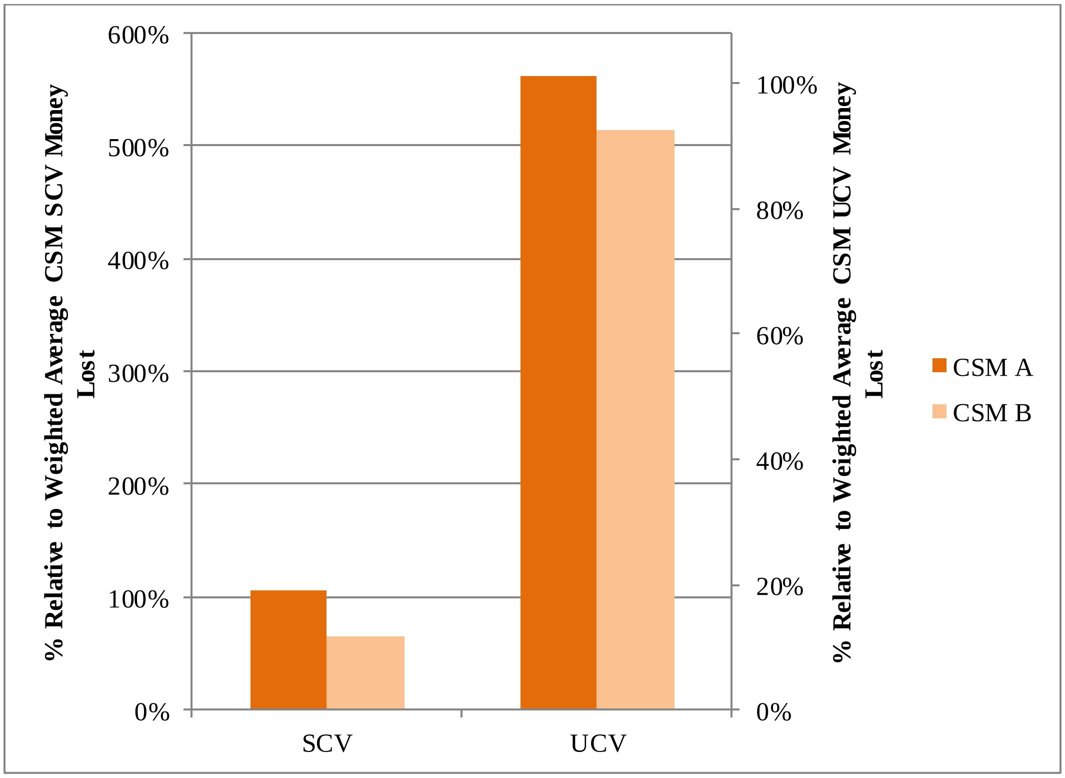

Figure 3.5: CSM SCV and UCV Money Lost Relative to Another

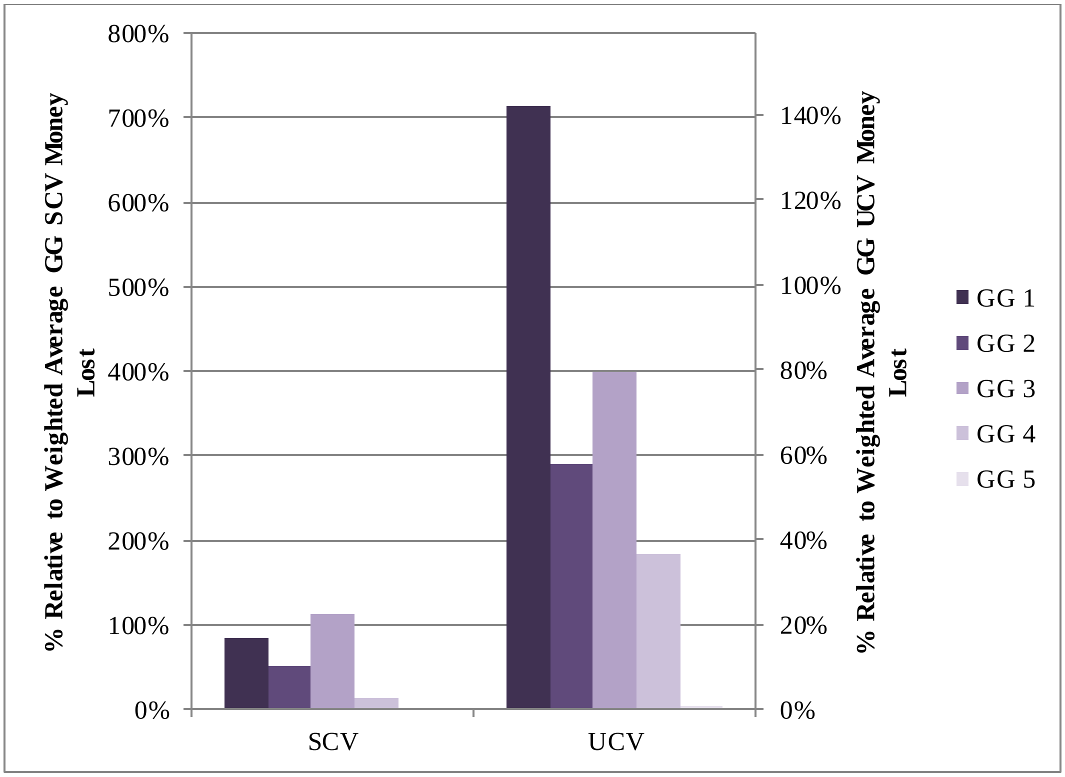

Figure 3.6: GG SCV and UCV Money Lost Relative to Another

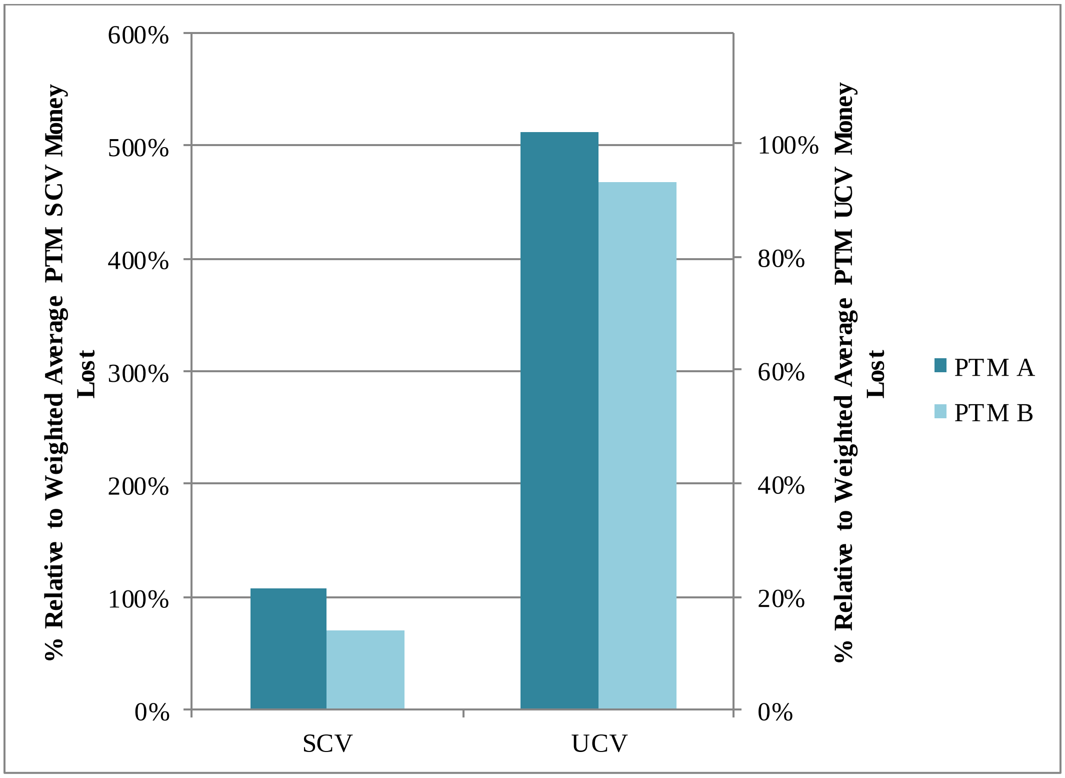

Figure 3.7: PTM SCV and UCV Money Lost Relative to Another

With EBR, all engines determined FR are inherently SCV since at least one part of that engine is serviceable. Yet with MBR, the modules may end up being SCV or UCV. The SCV and UCV came from the stock on hand values given in the AMCOM Integrated Priority List. These numbers were made into percentages and applied to each module to calculate the number of modules that would be determined SCV or UCV upon the CCAD inspector's analysis. This part of the analysis does not look at the repairs that can be done to each module upon its arrival to depot because it assumes that all remaining repairs can only be performed by depot-level maintainers, hence why it was returned to depot.

As it was explained in Section 3.2.1.4, the number of engines affected by each FR category can be determined by multiplying the annual engine demand for FY12 by the 13.91% of the engines that were determined FR and also by the FR category percentage from Table 3.2. For MBR, this number is used to find the annual money lost every time a serviceable module or unserviceable module is returned to depot. Again, the money lost is a sunk cost and it will be incurred every single time a module is returned to depot. In order to determine the annual money lost due to SCV module returns, the number of engines affected by each FR category is multiplied by the percentage of SCV for that specific module and multiplied by the money lost every time that SCV module is returned to depot. The process is the same to determine the annual money lost due to UCV module returns, but uses the UCV percentage and UCV money lost per module. The annual money lost for SCV and UCV are added together to determine the total money lost annually when returning a particular module to depot.

For example, if this analysis is being done for the ASM, the annual engine demand for FY12 would be multiplied by 13.91% of engines determined FR and also multiplied by 2.81% to get the number of engines affected by ASM replacement. The weighted average difference between AUP and SCV would be calculated as well as the weighted average difference between AUP and UCV. The number of engines affected by ASM replacement would be multiplied by the percentage of ASM that are SCV and then by the weighted average difference between AUP and SCV to yield the annual money lost due to SCV ASM returns to depot. This value would be added to the annual money lost due to UCV ASM returns to depot to get the total money lost annually when returning ASM to depot.

3.2.1.6 Material Cost Avoidance Benefit & Projected Cash Flow[r]

The material cost avoidance benefit is the difference between the current cost (EBR) and the new forecasted cost (MBR). Figure 3.8 shows the material cost avoidance benefit annually for each module relative to the cost of returning a single engine to depot.

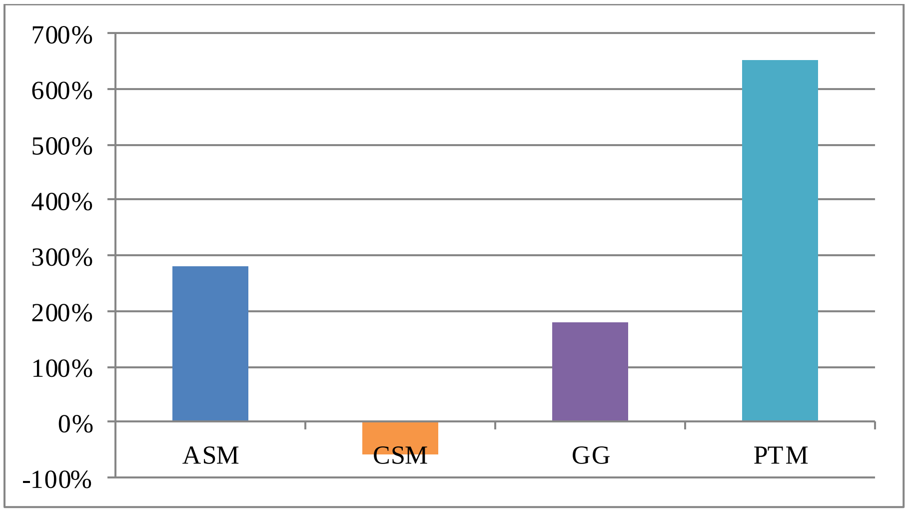

Figure 3.8: Annual Material Cost Avoidance Benefit for MBR Relative to a Single EBR Cost

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[r] Cash flow as used in this section refers to cash saved through material cost avoidance as explained herein

The only module with a loss is the CSM; alternatives to this outlier will be described in the following section. Even so, the annual money lost for sending in CSM over engines are about half of what it would cost to send in a single FR engine.

As mentioned previously, the first 3 bolded FR categories from Table 3.2 do not have material costs associated with them. Since these repairs will be performed instead of EBR, a material cost avoidance benefit exists. So, the new forecasted cost for these 3 categories is $0. Figure 3.9 shows the material cost avoidance benefit annually for each of the FR categories calculated. Similar to Figure 3.8, each FR category value is taken relative to the cost of returning a single engine to depot.

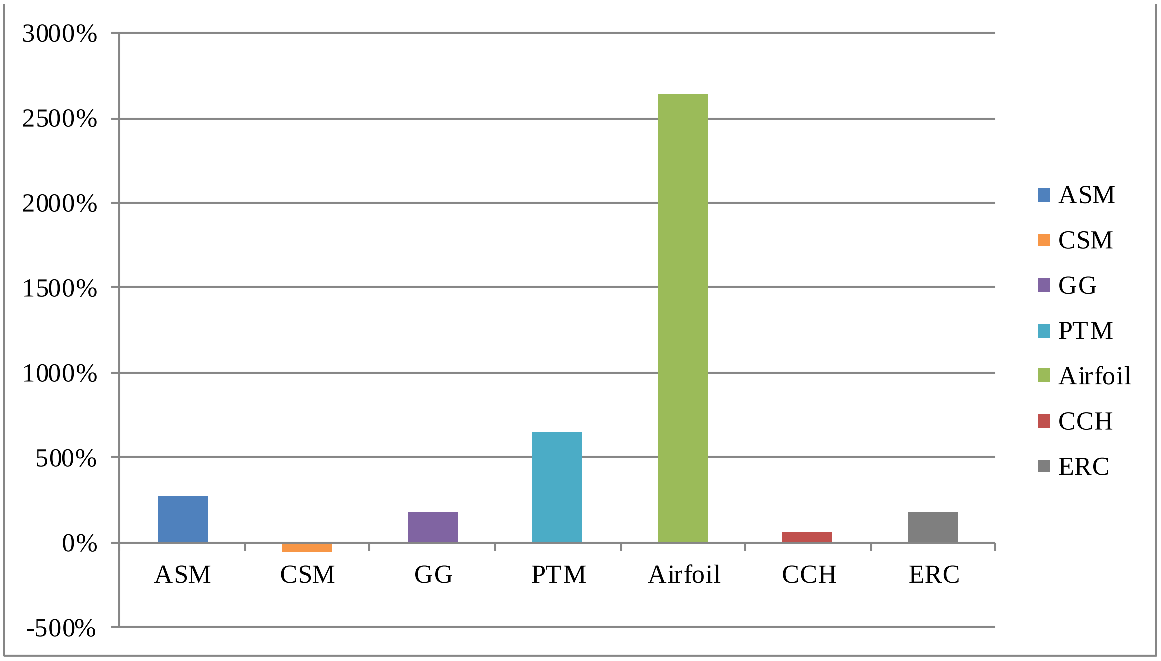

Figure 3.9: Annual Material Cost Avoidance Benefit for FR Categories Relative to a Single EBR Cost

Figure 3.10 displays the material cost avoidance benefit for each module along with its current and forecasted cost. This graph shows exactly how much of each EBR cost will be avoided by switching to MBR.

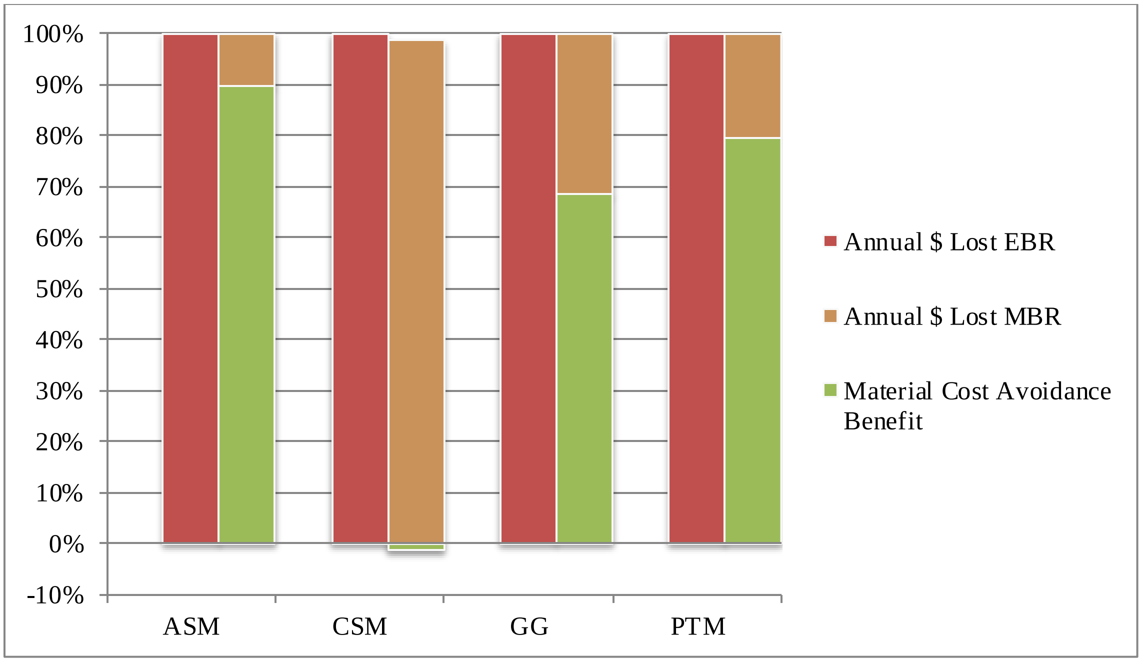

Figure 3.10: Bar Graph Displaying Material Cost Avoidance Benefit

The next step is to use the cost avoidance benefit to calculate the benefits achieved over a 10-year period of time. It is expected that the total benefit will not be seen in its entirety during Y1 but will be seen progressively. An incremental benefit of approximately 11.11% per year was chosen so that by Y10, a 100% benefit is achieved and engines will no longer be returned to depot in lieu of modules or other repairs. These calculations also take into account a 3% inflation rate, which was compounded for single flow, beginning in Y2. The inflation equation is mathematically expressed as:

$$F = P(F/P, i\,\%, N) = P(1+i)^N$$

where P is the present single sum, F is the future single sum, i is the interest per period in percent, and N is the period (beginning in Y1) [12]. The projected cash flow[s] over 10 years is illustrated on a graph in Figure 3.11. The graph shows exactly how much of each repair’s material cost avoidance benefit make up the total material cost avoidance benefit

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[s] Cash flow as used in this section refers to cash saved through material cost avoidance as explained herein

annually. These values are shown relative to the total material cost avoidance benefit calculated, allowing the total to be exceeded in Y9 due to inflation.

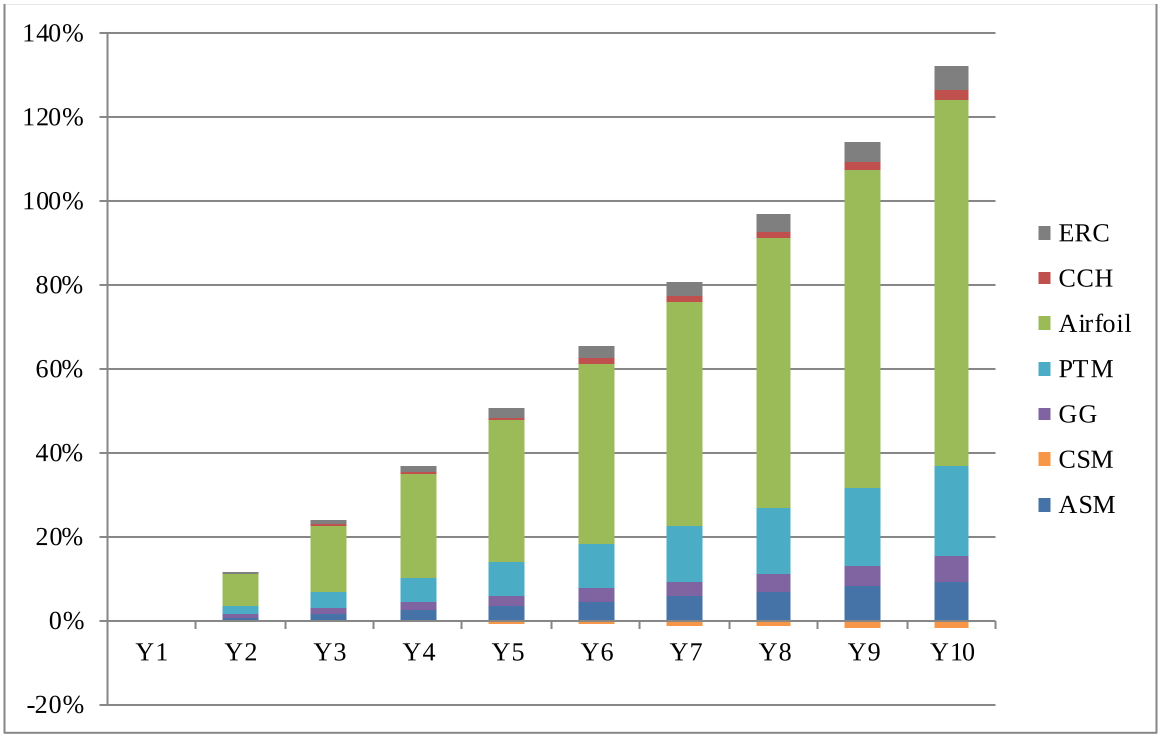

Figure 3.11: Annual Percentage of Material Cost Avoidance Benefit Achieved

3.2.1.7 Examining Specific Engine-Module Combinations

The utilization of weighted averages for the engines and modules allows the analysis to be simplified. Unfortunately, it does not show the material cost avoidance benefit of each combination of engine and module. As it was seen in Figure 3.3, these costs can vary greatly. Taking this into account, the analysis was executed again for every combination to highlight exactly the benefits that would be achieved with each set. Each material cost avoidance benefit combination is taken relative to the absolute value of the weighted average material cost avoidance benefit for each module. Using the absolute value allows any negative individual material cost avoidance benefit combinations to remain negative. Graphs illustrating this are shown below in Figures 3.12-15.

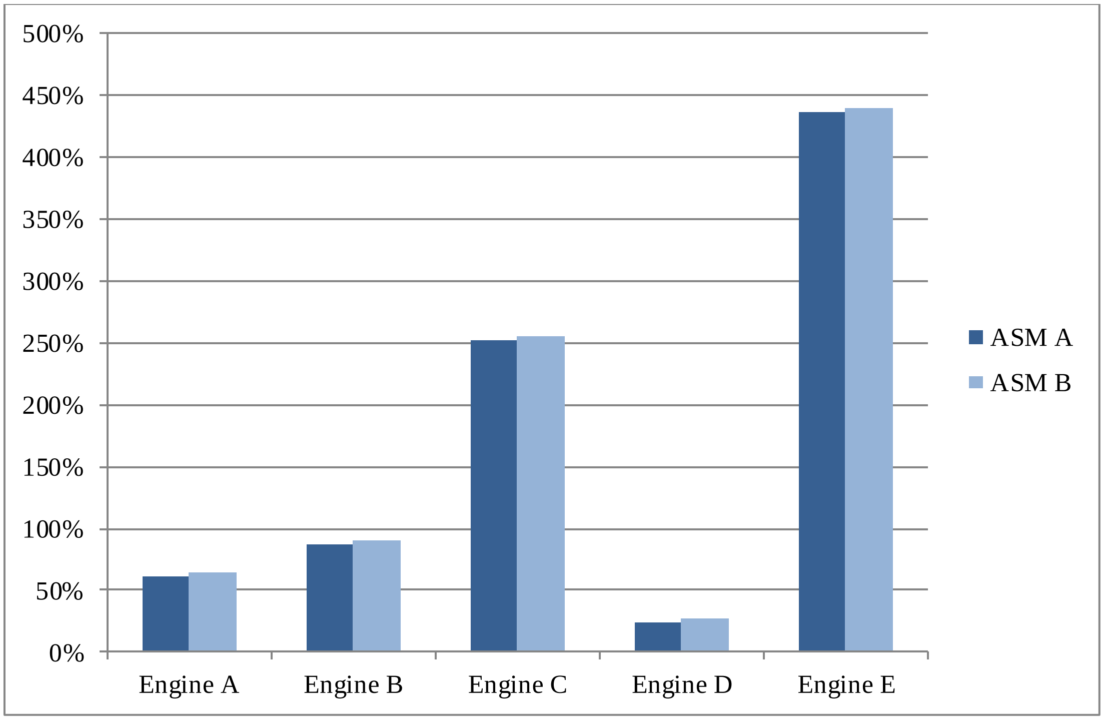

Figure 3.12: Material Cost Avoidance Benefit for Specific ASM-Engine Combinations

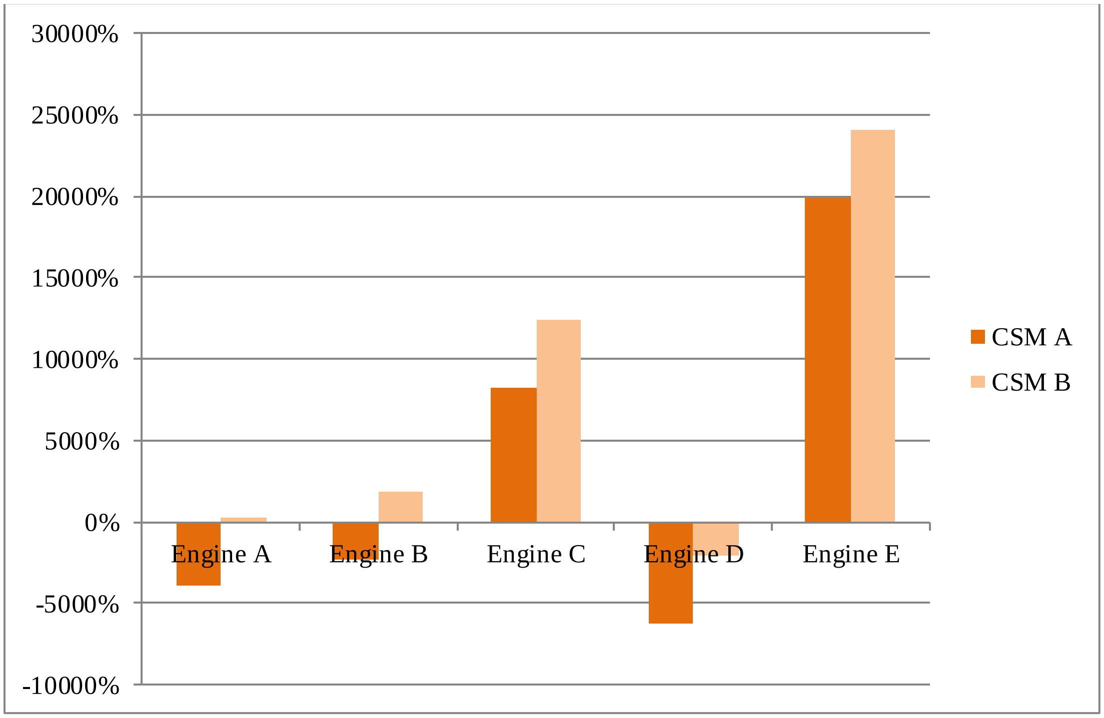

Figure 3.13: Material Cost Avoidance Benefit for Specific CSM-Engine Combinations

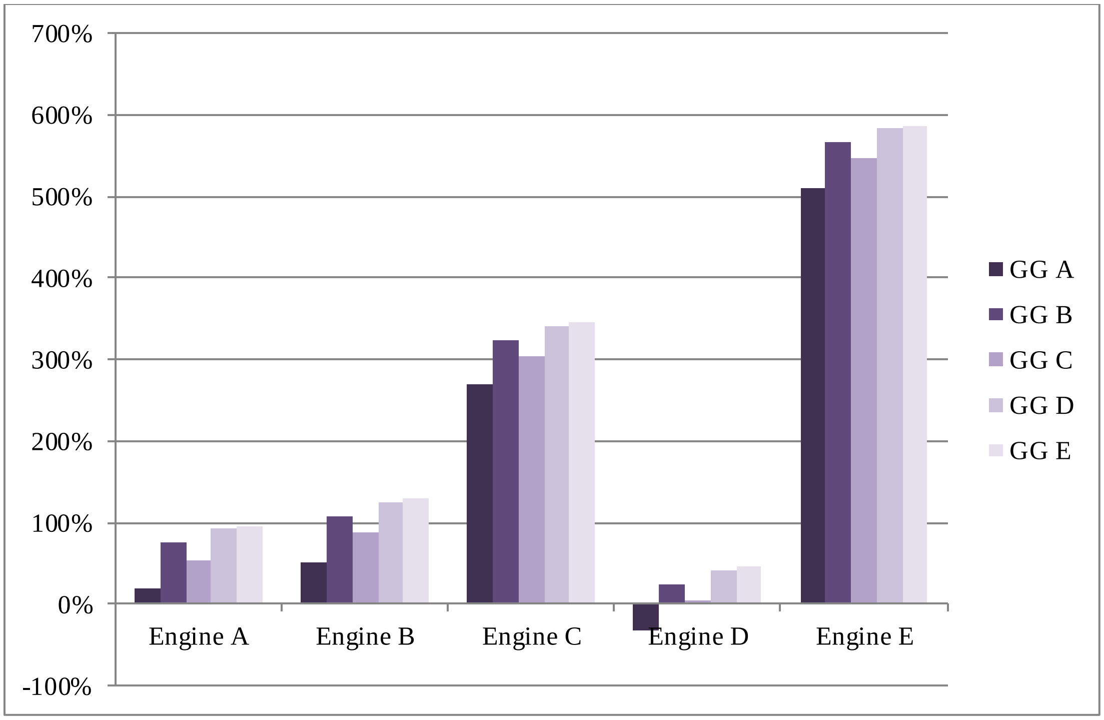

Figure 3.14: Material Cost Avoidance Benefit for Specific GG-Engine Combinations

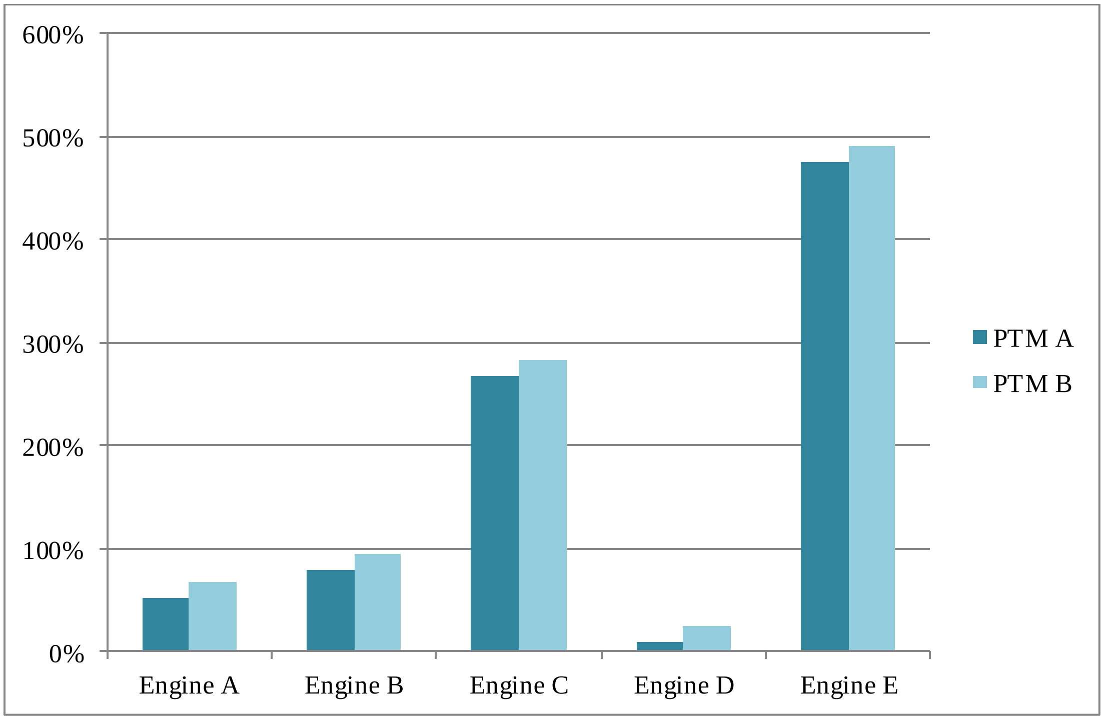

Figure 3.15: Material Cost Avoidance Benefit for Specific PTM-Engine Combinations

Looking at Figures 3.12 and 3.15, it can be seen that all of the values are positive. This means that for every engine-module combination, costs will be avoided by switching to MBR from EBR. Out of the 25 possible combinations in Figure 3.14, only Engine D and GG A yielded a negative material cost avoidance benefit. This one combination situation represents an insignificant additional cost in light of the overall material cost avoidance benefits in the 24 other possible combinations. Nonetheless, it should be noted that if a maintainer comes across a GG A and Engine D combination, it would be better to go ahead and replace the entire engine.

In Figure 3.13, 4 out of 10 possible combinations resulted in a negative material cost avoidance benefit. For these combinations, it is more cost efficient to send in the engine instead of sending in the CSM. It is recommended that the maintainer refer to these combinations when dealing with a depot-level CSM repair. As it can be seen with Engines C and E, these MBR yield a very high material cost avoidance benefit.

3.2.2 Operational Cost Avoidance

One major opposition to implementing MBR and emphasizing focus on the other repairs instead of just returning the engine to depot is the amount of time these repairs take. The only time that would be saved would be immediate. All of these repairs will eventually need to be made; the only difference is whether they are being made in the field or at depot. Returning the engines simply to have less downtime is not necessarily the best option, barring mission critical situations. Overall, it ends up costing more. Secondary costs include those incurred by Army Supply; people working in this department have to file the paperwork and send the engine out. Transportation fees are increased because the engine weighs significantly more than each module. Moving the engine across the country, and sometimes overseas, leaves potential for incurred damages along the way. Labor costs are increased because the original maintainers took the engine apart and put it back together just to have the same process repeated once it arrives at depot. Furthermore, it is likely that since depot-level maintainers have a higher level of training that they also have a higher salary. It would be more cost effective to have a lower level maintainer perform the repairs.

As a reference, the MMH for the engine and FR categories are given below in Table 3.4. The engine replacement is the only maintenance action that can be done by an AVUM-level maintainer; all others are AVIM-level.

Table 3.4: Total MMH for Engine & Field Repairable Categories

Component/Assembly	Maintenance Function	Total MMH
Engine	Replace	2.0
ASM	Replace	2.7
CSM	Replace	4.7
GG	Replace	4.8
PTM	Replace	3.3
Airfoils	Repair	9.5 – 12.7
CCH	Repair	6.8
ERC	Repair	11.5 – 14.7

According to the MAC, an engine replacement should take 2 hours. Since every other maintenance action listed requires engine removal, 2.0 hours has been added to each MMH total. ASM, CSM, and PTM replacement times are comprised of the MMH given for its specific module replacement as well as the 2.0 hours for engine removal. Since the GG Matched Assembly cannot be accessed without first removing the PTM, its total MMH includes engine replacement, PTM replacement, and replacing the GG Matched Assembly, which consists of the GG stator and stages 1 and 2 GG turbine rotor. As stated previously, the airfoils are within the CSM so its MMH total includes engine removal, CSM removal, and airfoil repair. CCH and ERC have estimated MMH. Since ETC consists of engines that need both exit rub blending and airfoil repair, the MMH for both are included. Exit rub blending is estimated at 2.0 hours. CCH are experienced in the GG Matched Assembly so an estimated 2.0 hours is added to the GG Matched Assembly total MMH.

3.2.3 Total Cost Avoidance Benefit

Typically, the total cost avoidance benefit is obtained by adding the material cost avoidance benefit and the operational cost avoidance benefit together. Since this analysis consists only of material cost avoidance benefit, that is what the total cost avoidance benefit will be. Figure 3.16 below displays the total annual costs before (EBR) and after (MBR) the maintenance protocol changes. Each cost is taken relative to the total annual cost before in order to highlight the cost avoidance achieved annually.

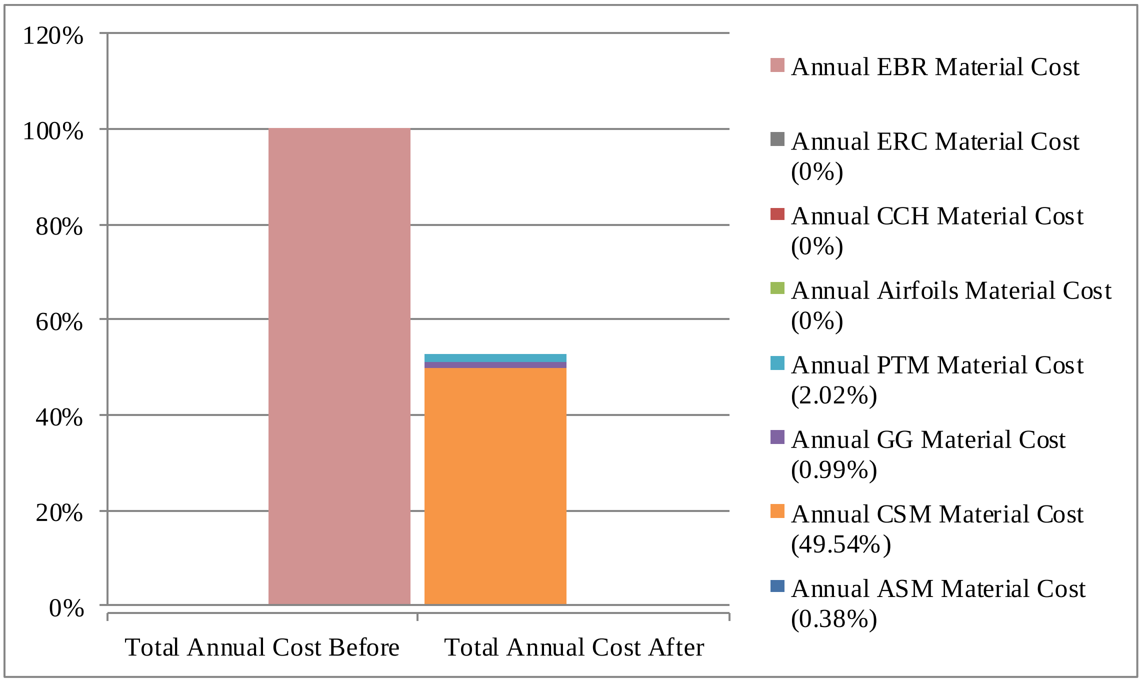

Figure 3.16: Total Annual Cost Before & After Maintenance Changes

As illustrated in Figure 3.16, the annual cost has been reduced by 47%. Additionally, the number of engines determined to be FR is reduced by over 75%. In other words, previously 13.91% of engines demanded annually were determined FR but with these changes, only 3.39% of engines are determined FR. Ways to reduce this number even more are discussed in the following section.

Figure 3.17 displays how much each FR category's total cost avoidance benefit comprises the total annual cost avoidance benefit.

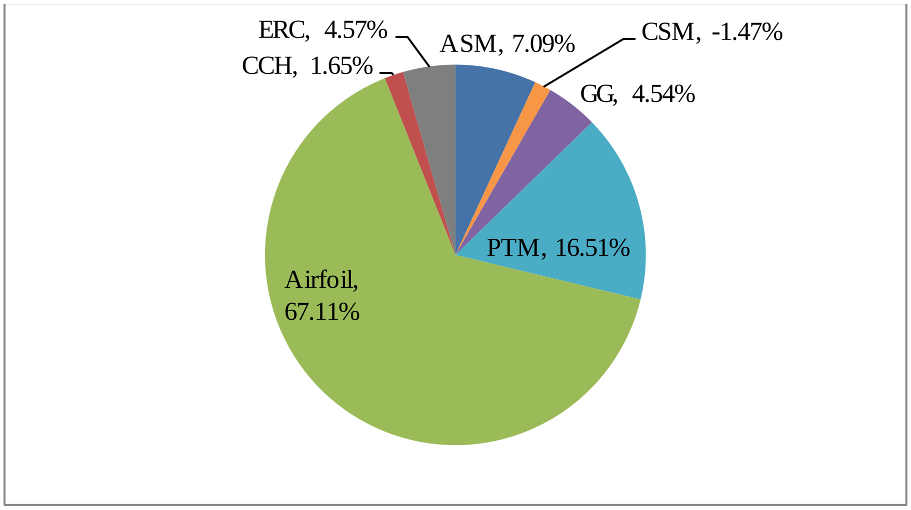

Figure 3.17: Total Annual Cost Avoidance Benefit by FR Category

3.2.4 Discussion of Other Field Repairable Categories

The analysis thus far has covered 7 out of the 13 FR categories given in Table 3.2. As a reference, the remaining 6 categories and their percentages of all FR engines are given below in Table 3.5 so that they can be examined closer.

Table 3.5: Remaining Field Repairable Categories

Compressor Stall	3.85%
Inserts, Studs, Bolts	4.59%
Leak	2.37%
Other	5.63%
Replacement	3.26%
Replacement – Combination	4.59%

Compressor stalls tend to be related to the control system and/or airbleed system. In order to resolve this issue, the maintainer should have followed troubleshooting procedures. The troubleshooting procedures lead to the replacement of certain LRUs. LRUs are line-replaceable units. This repair was not included in the analysis because troubleshooting should have been done in order to determine which LRU replacements were needed.

Engines returned to depot under the FR category "Inserts, Studs, Bolts" needed very simple repairs—to replace the insert, stud, or bolt that was missing from the assembly. All of these engines were determined to have nothing wrong with them aside from a small missing part. Installing a replacement part for each of these engines would have taken no more than 15 minutes.

The only solution for engines with leaks is troubleshooting. This would have led the maintainer to a maintenance action that could have been taken, most likely involving a part replacement. Engines within the category of "Other" are those with difficult-to-determine solutions based on the depot inspector's notes. The engines labeled "Replacement" are engines requiring minor AVUM or AVIM-level part replacements; many of these require LRU replacements. Lastly, the "Replacement – Combination" category includes engines that require more than one part replacement. This can mean multiple module replacements and/or replacements of a smaller nature.

Overall, each of these categories would likely result in a positive cost avoidance benefit. For the purposes of this analysis, the benefits are considered negligible and are not included.

3.3 Summary

It is evident that switching to module-based replacements from engine-based replacements will reduce the number of engines that are sent unnecessarily to the Army depot annually. EBR may seem to be more efficient as an immediate solution but in the long run, it is a massive cost burden. The maintenance burden moves from the more costly depot-level maintainer to the AVUM- or AVIM-level maintainer. Operations and support costs are reduced because modules are being returned to depot instead of the much larger engine. Keeping a higher stock of modules instead of engines allows aircraft readiness to remain high while avoiding unnecessary costs. To put it into perspective (based on the weighted average AUP of each engine or engine module), the cost of one new engine is equivalent to 7.65 ASM, 1.94 CSM, 5.90 GG, or 4.00 PTM.

Another way to reduce the number of FR engines sent to depot is to reassign certain depot-level tasks to lower maintenance levels. This would further reduce the operations and support costs and would allow AVUM- and AVIM-level maintainers to repair more engines and/or modules in-house rather than shipping them to CCAD.

Currently, 13.91% of engines demanded annually are sent to depot with repairs that could have been made in the field. By replacing modules instead of engines, this value can be cut in half. After implementing the other maintenance changes detailed, this number can be reduced even more to 3.39%. As a result, the annual cost of sending components to depot is reduced by 47%. With the turboshaft engine being the number one cost burden to the Army, this cost avoidance would be a significant achievement.

CHAPTER 4. CONCLUSION

The proposed research effectively demonstrates the various benefits that can be attained through condition-based maintenance practices. Through the ever-evolving world of technology, it is important to continually make changes to maintenance protocols. CBA methods can be applied to various situations to visualize the prospective gains that can be achieved through adjustments and improvements to current procedures.

Case Study I demonstrates the advantages to self-adhering elastomeric blade wedges over the current method of trim tab bending in rotor smoothing events. Not only do they maintain the same change in lift and pitching moment characteristics, but they also eliminate trim tab washout as a trailing edge failure. Wedges are quicker, easier and more accurate than bending metal tabs, for installation and use over time. Maintenance delay due to an absence of necessary equipment or trained maintainers is no longer an issue. The reduction in trailing edge failures experienced by main rotor blades leads to a decrease in overall main rotor blade demand. The demand decrease, as a material cost avoidance, comprises the majority of the total cost avoidance benefit. Due to the tracking accuracy of the wedges, maintenance test flight patterns flown during rotor smoothing events are reduced. The favorable material properties of the elastomer prevent the wedges from degradation during flight. Aircraft equipped with tracking wedges experience lower levels of vibration leading to the following benefits: less corrective maintenance actions, reduced downtime, lowered component failure rate, a reduction in removal and replacement rates, increased mean time between failure, increased reliability, increased availability, and increased maintainability. The analysis of both the material and operational benefits that are achieved from the use of elastomeric wedges as a form of vibration control result in a 10-year return on investment of between 9.8:1 and 23:1 for the current rate of flight and a range of projected peacetime flight hours.

Case Study II explores the benefits to module-based replacement and other changes to maintenance practices over engine-based replacement. The total cost avoidance benefit derives solely from the reduction of engines unnecessarily being sent to Army depot. Maintaining a higher stock of modules instead of engines prevents the impulse to return the entire engine to depot in order to maintain aircraft readiness. It allows the readiness to remain high while avoiding unnecessary costs. Reassigning certain depot-level tasks to lower maintenance levels would reduce the number of field repairable engines sent to depot. O&S costs would be reduced by keeping more engine/module repairs in-house rather than shipping the components to CCAD for repair. Currently, 13.91% of engines demanded annually are sent to depot with repairs that could have been made in the field. By replacing modules instead of engines, this value can be cut in half. After implementing the other maintenance changes defined, this number can be reduced even more to 3.39%. As a result, the annual cost of sending components to depot is reduced by 47%. With the turboshaft engine being the number one cost burden to the Army, this cost avoidance would be a significant achievement.

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