Cost-Wise Readiness Enabled Through Condition Based Maintenance Plus (CBM+)

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ABSTRACT

As Department of Defense (DoD) budgets continue to decrease through automatic spending cuts, Army Commands are pressured to develop, implement and manage new ways to reduce spending. The high cost of operation and sustainment (O&S) associated with the helicopters required to support the US Army's global presence significantly increases this pressure. Reducing costs within O&S activities, while managing operational readiness is achieved through Cost Wise Readiness (CWR) initiatives. Goals and objectives are to increase efficiencies, thereby increasing the value of each budgeted dollar. Even as the budgetary environment becomes more challenging, the purpose of Army maintenance remains unchanged—to generate combat power. In support of continuing this capability, Army Aviation is leading the way with ongoing efforts to implement, measure and communicate efficiencies leading to benefits. The AMCOM Logistics Center (ALC) functions as the logistics component of the US Army's Aviation and Missile Life Cycle Management Command (AMCOM) headquartered at Redstone Arsenal, Alabama. The ALC develops, acquires, fields and sustains logistics support for Army Aviation and Missile systems and associated support equipment to ensure weapon system readiness in any operation worldwide. The ALC, in support of Program Executive Offices, Project Managers, Army Depots, and partnering with industry are dedicated to provide real-time logistics support to the Soldier, Airman and Marine in training and combat. The ALC is dedicated to the development and implementation of CWR initiatives through the identification and pursuit of opportunities and investment in projects focused on reducing cost. Multiple Army offices have been instrumental in the development of technological capabilities in support of the CWR mission. One such high-tech capability includes the integration of systems which incorporate Condition Based Maintenance Plus (CBM+) into the management of logistics and airworthiness aspects of the Army's helicopter fleets. Managing costs within O&S activities is achievable through the remediation of maintenance enabled through CBM+ initiatives.

1. INTRODUCTION

The challenge of declining defense budgets require the development of exceptional techniques to cut O&S costs. Overseas Contingency Operations (OCO) funding continues to be reduced from prior enacted levels. CBM+ supports the automation of monitoring the condition of certain components, therefore allowing for noteworthy remediation of oftentimes very conservative time based parts replacement practices. The technology enables significant cost benefits by facilitating time between overhaul and retirement change life limit extensions authorized for certain components. This supports reduced component replacement frequency, thereby cutting material costs, while enhancing mission readiness and efficiency by decreasing the Warfighter's maintenance burden by automating routine inspections. This paper details how results of implementing CBM+ initiatives are calculated. The Army's use of CBM+ technology, chiefly by the Apache PMO and its AH-64 aviation units, has supported the goal of CWR as a top objective of the ALC. One goal of the Supportability and Sustainment Directorate (SSD), Sustainment Optimization & Analysis (SOA) - Assessment Division is to support this mission by substantiating CWR benefits.

2. BACKGROUND - ISSUES BEHIND COST DRIVERS

In the interest of airworthiness, and to keep baseline risk well beneath accepted levels, maintenance procedures require multiple and frequent condition inspections, Maximum Allowable Operating Time (MAOT) and Time between Overhaul (TBO) intervals. The maintenance interval requirements are oftentimes extraordinarily conservative, as they are based upon preserving safety margins which were defined long before CBM monitoring systems were developed or installed on legacy aircraft. Therefore, in order to act according to established requirements, it has long been compulsory to take maintenance actions on equipment prior to MAOT and/or TBO before any evidence of need exists,

regardless of the actual remaining useful life. For decades, extraordinarily conservative safety margins have imposed millions in added costs to O&S activities throughout the Army's helicopter fleets.

One cost driver was the prior, ultraconservative MAOT of the AH-64D Main Transmission Accessory Sprag Clutch. It remained particularly high for well over a decade after trouble was caused by the dual failure of both the primary and the secondary Accessory Gearbox Sprag Clutches. The clutches experienced unanticipated early wear each triggering critical failure modes.
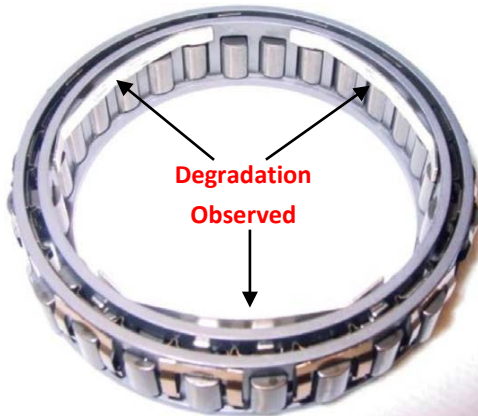

Figure 1. Transmission Accessory Gearbox Sprag Clutch

AH-64D Main Transmission Accessory Sprag Clutches provide the mechanical power input to critical accessory systems. The TBO of the transmission, to include its clutches was originally greater than 2000 hours. However the clutches were knocked down to a much more conservative 1000 hour MAOT limit following an airworthiness determination made in the late 1990s. This constricted life limit significantly increased O&S costs over the years since. In accordance with Army Regulation 700-82, the clutch is only replaceable at the depot maintenance level. Therefore, the main transmission had to be removed and replaced every 1000 hours, elevating maintenance burden fleetwide. Figure 1 above illustrates the affected areas that have historically caused limited life.

In July 2011, an additional the 1000 hour TBO was increased to 1250 hours, and again from 1250 to 1500 hours in April 2013. Substantial benefits have resulted from the increases. Additional AH-64 Apache components granted similar TBO and life extensions are also included in this manuscript. Each extension has been measured similarly and were each implemented through the outstanding efforts of all US Army Aviation offices which collaborated to execute the efforts to reduce burden and cost.

3. O&S COST MITIGATING REMEDIATION PROJECTS

Achieving authorization to extend MAOT and TBO intervals of components requires well-structured collaboration between the several Army organizations. Included in these efforts were the AH-64D Apache Helicopter, MSPU, and components' original equipment manufacturers (OEM), the Aviation and Missile Research Development and Engineering Center (AMRDEC) Aviation Engineering Directorate (AED) and Engineering Directorate (ED), the Apache Attack Helicopter (AAH) Program Management Office (PMO), the Program Executive Office-Aviation (PEO-A), along with other Team Redstone offices, including Redstone Test Center (RTC) and the AMCOM G3 CBM Office. Each office was responsible for key elements which have led to several highly valuable fleet wide extension authorizations. The University of S. Carolina (USC) CBM Test Center and the S. Carolina Army National Guard (SCARNG) provided fundamental support for successes generated. Algorithms were developed through meticulous refinement efforts in accordance with the criteria defined in the ADS-79 Handbook. Multiple teardown inspections were accomplished. This ensures that the quantity of false positives, false negatives and other indications were reduced to a minimum. Teardown inspections were conducted through the coordination of AED, RTC, and the OEM. Each was essential to ensure the fielding of reliable algorithms; the kind of algorithms that maintainers could depend on to provide correct indications regarding the condition of parts, and aircrews could depend on to save lives.

TBO and MAOT imitations were primarily set through the conventional reliability analysis processes, before development of condition monitoring capabilities. The successful fleet wide extension of safe and valuable extensions required iterative processes of data analysis, laboratory testing, followed by limited fielding on actual helicopters. Further analysis was executed to complete detailed test plans. Test fixtures were designed to accommodate the need to develop and validate highly reliable CIs in accordance with ADS-79. RTC and the USC CBM Test Center were each utilized to execute laboratory and testing and to conduct collaborative tear down analysis (TDA) with AED. TDAs are essential to the development of and validation of CIs. Teardown evaluations continue through the RIMFIRE process at the Corpus Christi Army Depot. RIMFIRE stands for Reliability Improvement through Failure Identification and Reporting.

4. APPLICATION OF CBM & ASSOCIATED CHALLENGES

Army Aviation's application of CBM onto its multiplatform fleets of helicopters has not been without its various challenges. For the last 10 years, many advocates have led the way and overcome challenges. Some of the early challenges included funding the installation program. With no specific requirement, coupled with limited time and funding, user training has been most challenging.

Proper data management involves very complex tasks. The data must not only be collected and transmitted, but stored and

analyzed in a useful manner so as to provide actionable information to the maintenance officer. As one of the most high tech platform users, Apache Helicopter units have led the way in terms of managing each one of these complicated tasks. The Apache also has the highest percentage of Digital Source Collectors (DSC) installed, and the most mature Condition Indicators (CI) of all Army helicopter platforms. The Aeronautical Design Standard Handbook Condition Based Maintenance System for US Army Aircraft (ADS-79D) defines a CI as "A measure of detectable phenomena, derived from sensors, that shows a change in physical properties related to a specific failure mode or fault."

CIs are extremely challenging to mature to the required confidence level. The ADS-79D defines this as follows: The probability that a confidence interval contains the true value of a population parameter of interest. When not otherwise specified in this ADS, the confidence level should be assumed to equal 0.9 (or 90%)." Any less and conditions indicated by the CI could be highly questionable or disregarded.

5. MEASURING AND COMMUNICATING CBM+ BENEFITS

In coordination with the Apache Attack Helicopter (AAH) Project Management Office (PMO), the Army Aviation and Missile Command (AMCOM) Logistics Center (ALC) has established the Post Implementation Assessment (PIA) capability. The methodology provides the Army with a repeatable technique to measure implemented projects' tangible and traceable benefits. The methodology measures how CBM technology has enabled significant increases in efficiency, supplementing improved operational readiness rates. The dedicated participation and practical employment of the technology by Army Aviation battalions, particularly by the Apache Attack Helicopter Project Management Office and AH-64 aviation units is clearly demonstrated, and has supported ALC in its every day mission and objective to achieve its goal of CWR initiatives. As an example, the team collaborated with other Army Aviation offices to substantiate the benefits from an ongoing CBM project, one which has successfully extended the AH-64D Main Transmission time between overhaul (TBO) and its internal Sprag Clutches' MAOT limit. CBM benefit metrics from these flight hour extensions have been identified and calculated. The goal of ALC's Post PIA methodology is to fulfill the requirement to capture and communicate the benefits of CBM+. The PIA methodology does this by identifying the primary known benefit contributors. As with any globally deployed complex vehicles with high cost and maintenance requirements, large fleets of Army Helicopters have multiple efforts working in parallel, each aimed at generating combat power while decreasing soldier burden, demand, and cost through increasing installed components Time on Wing (ToW).

Fleet wide performance metrics of each implemented project are measured regarding: 1) The sum total costs assessed since implementation; 2) The average cost since implementation; 3) Demand reduction per 10,000 flying hours (FH); 4) ROI. All performance metrics are updated quarterly basis to continue measuring performance metrics as extensions remain valid

and continue producing statistically significant benefits. Calculations to measure benefits include:

6. DATA ELEMENT DEFINITIONS

6.1. Demands

Demands (D): Item's quantity of demands at the retail level during a timeframe before and after implementation. Demand data is pulled from the ILAP (Integrated Logistics Analysis Program) database.

6.2. Flight Hours

Flight Hours (FH): The quantity of flight hours flown during the same timeframe before and after implementation. FH data is Department of the Army (DA) Form 1352 data pulled from the Logistics Information Warehouse (LIW) and utilizing the Readiness Integrated Database (RIDB) application.

6.3. Exchange Price

Exchange Price (EP): The item's price at the unit level for each year in the calculation. The EP includes current pricing as well as prior archived FY pricing (when available) and is pulled from the Logistics Modernization Program (LMP).

6.4. Base Line Time Period

Base Line (bl - appears as lower case in the calculation): The base line time period is two years prior to implementation unless otherwise identified.

6.5. After Implementation Time Period

After Implementation (ai - appears as lower case in the calculation): The time period since implementation, when data becomes statistically significant.

6.6. Rate of Demands

Rate of Demands (RD): The quantity of unit Demands as normalized per 10,000 FH for the Time Period (tp - appears as lower case in the calculation i.e. Baseline Rate of Demands appears as "RD_{bl}").

6.7. Expected Demands

Expected Demands (ED): A representation of the quantity of unit Demands that would have occurred after implementation using RD_{bl} as calculated through the multiplication of each fiscal year's (FY) actual FH.

6.8. Average Cost per Flight Hour

Average Cost per Flight Hour (ACFH): The cost calculated by multiplying the sum of each applicable FY's unit Demand times the EP, divided by the sum of all associated FHs across the same FYs.

6.9. Cost Assessment

Cost Assessment (CA): The value of the monetized benefits yielded in terms of material demand changes as calculated during the specified time period after implementation of a project.

6.10. Additional Time on Wing

Additional Time on Wing (Tow): The quantity of additional flight hours a component remains installed on a system in operation, i.e. through TBO and/or MAOT extensions. Computed using AMCOM Message Tracking System (AMTRACKS), DA 1352, DA 2410 (Component Removal and Repair/Overhaul Record) databases to calculate the sum of actual hours flown above the base line life limit using the criteria in the message extending the life limit.

6.11. Additional Demands Based on Additional ToW

Additional Demands (AdD): A representation of the quantity of additional demands that would occur after implementation using baseline RD_{bl}.

6.12. Adjusted ACFH with Added Demands

Adjusted ACFH with Added Demands (AdACFH): The cost per FH after implementation, adjusted to include the ED.

6.13. Cost Benefit

Cost Benefit (CB): The value of the overall project implementation as it relates directly to the specific change fielded through the project undergoing assessment (e.g. TBO extension), in terms of the change in supply cost during the time period after implementation, as referenced against the baseline time period.

6.14. Cost Benefit per Cost Assessment

Direct Cost Benefit per Cost Assessment (CB/CA): The percentage of the overall Cost Assessment yielded during the time period after implementation which can be attributed directly to the change implemented by the project undergoing assessment.

6.15 Return on Investment

Return on Investment: A performance measure used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. To calculate ROI, the benefit (return) of an investment is divided by the cost of the investment; the result is expressed as a ratio. The PIA process includes two levels or ROI, as explained below:

6.15.1 Overall Cost Assessment ROI

Overall Cost Assessment ROI: The ratio of Demand Cost Assessment minus the Project Investment divided by the Project Investment. Overall Cost Assessment ROI cannot be fully attributed to the project undergoing assessment. Further calculations are required to formulate the project's Direct ROI, as noted below.

6.15.2 Direct ROI

Direct ROI: The ratio of Cost Benefit minus the Project Investment divided by the Project Investment. Direct ROI is intended to formulate the project's Direct ROI

7. COMPUTATIONS WITH DEMONSTRATIVE EXAMPLES

It should be noted that each example demonstrated below include fictitious figures in terms of demand, flight hours, prices and cost. These fictitious quantities are included below in Figure 2, with the objective is to avoid issues relative to applying actual figures, and the goal is to show how data elements are applied to advanced formulas.

Figure 2. Post Implementation Assessment Example

7.1. Rate of Demands: Base line & After Implementation

7.1.1. Base line Rate of Demands

As an example, using fictional figures, the Baseline (bl) Rate of Demand (RD_{bl}) before implementation is 13.16 Demands (D) per 10K FH, calculated as follows: D = 325 units from 1 Oct 2010 through 30 Sep 2011 (FY11), and FH = 250,000 for the same period; and for from 1 Oct 2011 through 30 Sep 2012 (FY12): D = 300 units from 1 Oct 2011 through 30 Sep 2012, and FH = 225,000 for the same period.

$$RD_{tp} = \frac{\sum_{m=1}^{n} D_m}{\sum_{m=1}^{n} FH_m * .0001} \qquad (1)$$

$$RD_{bl} = \frac{(325+300)}{(250,000+200,000)* .0001} = 13.16 \text{ demands per 10K FH}$$

7.1.2. Rate of Demands After Implementation

As an example, using conceptual figures, the After Implementation (ai) RD (FY13 & FY14) is 10.84 demands per 10K FH, calculated as follows: FY13 D = 250 units and FH = 215,000; and FY14 D = 200 units and FH = 200,000.

$$RD_{tp} = \frac{\sum_{m=1}^{n} D_m}{\sum_{m=1}^{n} FH_m * .0001} \qquad (2)$$

$$RD_{ai} = \frac{(250+200)}{(215,000+200,000)*.0001} = 10.84 \text{ demands per 10K FH}$$

7.2. Avg Cost per FH Baseline & After Implementation

7.2.1 Average Cost per FH Average Cost per FH

As an example, using fictional figures, the baseline Average Cost per Flight Hour (ACFH) is $404.61; calculated as follows: FY11 D = 325 units, FH = 250,000 and Exchange Price (EP) = $150,000; FY12 D = 300 units, FH = 225,000 and EP = $157,500:

$$ACFH_{tp} = \frac{\sum_{fy=1}^{n} D_{fy} * EP_{fy}}{\sum_{fy=1}^{n} FH_{fy}} \qquad (3)$$

$$ACFH_{bl} = \frac{(325*\$150,000)+ (300*\$157,500)}{(250,000+225,000)} = \$404.61 \text{ per FH}$$

7.2.2 ACFH After Implementation

As an example, using fictional figures, the ai Average Cost per Flight Hour (ACFH) is $292.04; calculated as follows: FY13 D = 250 units, FH = 215,000 and EP = $141,750; FY12 D = 200 units, FH = 200,000 and EP = $127,575:

$$ACFH_{tp} = \frac{\sum_{fy=1}^{n} D_{fy} * EP_{fy}}{\sum_{fy=1}^{n} FH_{fy}} \qquad (4)$$

$$ACFH_{ai} = \frac{(250*\$215,000)+ (200*\$127,575)}{(215,000+200,000)} = \$146.87 \text{ per FH}$$

7.3. Expected Demands

As an example, using fictional figures, Expected Demands (ED) for FY13 is 282.9, calculated as follows, when RD_{bl} = 13.16, FY13 FH = 215,000 and FY14 FH = 200,000.

$$ED_{tp} = \sum_{m=1}^{n} FH_m * (RD_{bl} * .0001) \qquad (5)$$

$$ED_{ai} = \left(13.16\left(\frac{215,000}{10,000}\right)\right) = 282.89 \text{ (FY13)}$$

$$ED_{ai} = \left(13.16\left(\frac{200,000}{10,000}\right)\right) = 260.00 \text{ (FY14)}$$

7.4. Cost Assessment

As an example, using fictional figures, the Cost Assessment (CA) is calculated as follows, when RD_{bl} = 13.16, FY13 D = 250 units, FH = 215,000 and EP = $141,750; FY12 D = 200 units, FH = 200,000 and EP = $127,575:

$$CA_{ai} = \sum_{fy=1}^{n} \left(RD_{bl}\left(\frac{FH_{fy}}{10,000}\right) - D_{fy}\right) EP_{fy} \qquad (6)$$

$$CA_{ai} = \left(13.16\left(\frac{215,000}{10,000}\right) - 250\right)\$141,750$$
$$+ \left(13.16\left(\frac{200,000}{10,000}\right) - 200\right)\$127,575$$

$$CA_{ai} = (282.29 - 250) * \$141,750 + (260.00 - 200) * \$195,887$$

$$CA_{ai} = \$4,662,829(FY13) + \$7,654,500(FY14) = \$12,317,329$$

7.5. Additional Demands Based on Time on Wing (ToW)

As an example, using fictional figures, Additional Demands (AdD) is based on Additional Time on Wing (ToW), calculated as follows, when FY13 Additional ToW is 20,000 FH and RD = 11.63, and when FY14 Additional ToW is 35,000 FH and RD = 10.84. Therefore, 58.3 (23.3+35.0) fewer units were required in FY13 and FY14 as a direct result of the 55,000 Additional ToW FH since TBO was extended.

$$AdD_{tp} = \frac{ToW_{tp} * RD_{tp}}{10,000} \qquad (7)$$

$$AdD_{fy13} = \frac{20,000*11.63}{10,000} = 23.26$$

$$AdD_{fy14} = \frac{35,000*10.84}{10,000} = 35.00$$

7.6. Adjusted ACFH per ToW

$$AdACFH_{tp} = \frac{(D_{tp} + AdD_{tp}) * EP_{tp}}{FH_{tp}} \qquad (8)$$

$$AdACFH_{fy13} = \frac{(250 + (\frac{20,000 * 23.26}{10,000})) * \$141,750}{215,000}$$
$$= \$180.16$$

$$AdACFH_{fy14} = \frac{(200 + (\frac{35,000 * 35.00}{10,000})) * \$127,575}{200,000}$$
$$= \$149.90$$

7.7. Cost Benefit

As an example, using fictional figures, the Cost Benefit (CB) is calculated as follows:

$$CB_{tp} = \sum_{fy=1}^{n} (ACFH_{bl})ToW_{fy} \qquad (9)$$

$$CB_{fy13} = \$180.16 * 20,000 = \$3,603,164$$

$$CB_{fy14} = \$149.90 * 35,000 = \$5,246,522$$

7.8. Cost Benefit per Cost Assessment

$$CB_{TP} = \frac{CB_{TP}}{CA_{TP}} \qquad (10)$$

$$CB_{fy13} = \frac{\$3,603,164}{\$4,662,829} = 77.3\%$$

$$CB_{fy14} = \frac{\$5,246,522}{\$7,654,500} = 68.5\%$$

7.9. Return on Investment

$$ROI_{tp} = \frac{CB - PI}{PI} \qquad (11)$$

$$ROI_{fy13} = \frac{\$3,603,164 - \$2,000,000}{\$2,000,000} = 0.8 : 1$$

$$ROI_{fy14} = \frac{\$5,246,522 - \$2,000,000}{\$2,000,000} = 1.62 : 1$$

$$ROI_{15} = \frac{\$9,088,015 - \$2,000,000}{\$2,000,000} = 3.5 : 1$$

8. ADDITIONAL AH-64 CBM+ ENABLED COMPONENTS

Figure 3. AH-64D Presenting Parts Remediated with CBM+.

9. CONCLUSIONS

Maintenance improvements enabled through implementation of CBM+ projects featured in this report have resulted in substantial benefits. However, it is important to note that the results require time and hundreds of thousands of FHs to materialize. While implemented maintenance changes featured in this report include only those applied to the Apache airframe, similar work is being pursued across the Black Hawk and Chinook platforms to support CWR through the reduction of materiel costs.

ACKNOWLEDGEMENT

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BIOGRAPHIES

Josh Kennedy is the Associate Director, ALC SSD SOA with over 24 years of experience in Army operations and unit leadership. Education includes a West Point Engineering B.S. degree, and multiple M.S. degrees, that include Aeronautical Science earned at the Embry-Riddle Aeronautical University (ERAU) and in Operations Research/Human Systems Integration earned at the U. S. Naval Postgraduate School. Recent studies include an Intermediate Level Education from the Army Command and General Staff College. As a results-oriented, Soldier-focused program manager, systems engineer, operations research analyst, and military officer he has a proven record of accomplishment in the fields of DoD weapons systems acquisition, Operations Research/Systems Analysis (ORSA), Human Systems Integration (HSI), strategic planning, analysis, and Test and Evaluation (T&E) efforts for new, multi-billion dollar Army Aviation systems. Josh is also recognized as a subject matter expert in project management and systems analysis regarding its connections to the DoD Systems Acquisition framework.

Jim Carter works as a Senior Reliability Engineer in the AMRDEC RAM Division, specializing in component survivability analysis. He received a Bachelor of Science Degree in Industrial Engineering from the University of Missouri, Columbia.

Matt Carter provides Systems Engineering Technical Assistance (SETA) contractor support to the ALC SSD SOA Assessment Division, and is an employee-owner at Modern Technology Solutions, Inc. (MTSI). For 21 years, experience has included wide ranging engineering support of multiple Army and Naval Aviation programs, including roles such as Sr. Electrical Engineer at the Sikorsky Aircraft Corporation, L-3 Communications, Raytheon, and Sr. Systems Engineer at

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