Conditioned-Based Maintenance at USC - Part IV: Examination and Cost-Benefit Analysis of the CBM Process

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Abstract

Our fourth component of research is focusing on expanding the Cost and Benefit Analysis (CBA) has been carried out to reflect on the whole CBM roadmap. This includes the cost savings in parts cost, operational support, the increase in mission capability rates, the decrease in scheduled and non-scheduled maintenance, and the increase in total flight time. It will also include the non-tangible benefits such as confidence for early diagnosis, attention and performance, personnel morale, actual safety and sense of safety. As of today, our activities have been highlighted by the following results and benefits; 1) Savings in parts costs: $1.4 million, 2) Savings in parts cost and operation support: $2.1 million, 3) Increased mission capable rates through a decrease in maintenance test flights and an increase in total flight time, 4) Improved safety, sense of safety, morale, and performance, and 5) meeting CBM objectives.

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Background

History

Since 1998 the University of South Carolina (USC) and the South Carolina Army National Guard (SCARNG) have participated in a number of important projects that were directed at reducing the Army aviation costs through improved logistics technology, better data management, and prompt decision making. This modern aviation maintenance transformation produces higher operational readiness using fewer, more capable resources, provides commanders with relevant maintenance-based readiness information at every level, and shifts the paradigm from preventative and reactive practices to proactive analytical maintenance processes, now commonly referred to as Conditioned-Based Maintenance (CBM). Per the Office of the Secretary of Defense (OSD), CBM is defined as "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."

The Commander of AMCOM supports the unprecedented transformation from the Industrial Age to the Information Age using existing and emerging technologies that analyze near real-time aviation systems data to provide prediction and response maintenance capability. Several technological advances and initiatives by Army leaders at various levels have made a move toward CBM a reality for Army Aviation. The benefits of these technologies have already been proven for helicopter on combat missions, training, and maintenance flight conditions. Considering the long history of participation with health monitoring systems and data collection, the University of South Carolina is in a position to provide leadership, vision, and a path forward to maximize the effectiveness of these benefits across the broad spectrum of Army Aviation.

The transition to CBM requires a collaborative effort on a massive scale and is contingent on identifying and incorporating enhanced and emerging technologies into existing and future aviation systems. This will require new tools, test equipment, and embedded on-board diagnosis systems. Even more critical, the transition to CBM involves the construction of data-centric, platform-operating capabilities built around carefully developed robust algorithms. This will allow soldiers in the field, support analysts, and engineers the ability to simultaneously, and in real-time, translate aircraft conditional data and proactively respond to maintenance needs based on the actual aircraft condition.

The University of South Carolina has supported the U.S. Army by conducting research to support timely and cost-effective aircraft maintenance program enhancements. Research emphasis has been to collect and analyze data and to formulate requirements for and assist in the transition toward Condition-Based Maintenance for the Armed Forces.

Program Objectives

The research program at USC seeks to deliver results which directly contribute to CBM efforts and objectives as follows:

- Link and integrate maintenance management data with onboard sensor data with test metrics and to quantify the importance of each data field relative to CBM
- Understand the physics and the root causes of faults of components or systems
- Explore the development of models for early detection of faults
- Develop models to predict remaining life of components and systems.

Program Processes

These program goals will be accomplished through the following processes:

- Quantitatively operationalize the CBM objectives through our ongoing quantitative ULLS-A and vibrations data that we are collecting, analyzing, and processing for the last six years. The most obvious outcome of these activities is the cost benefits and mission benefits models. Other ongoing activities will include value engineering process of the system in meeting CBM objectives.
- Qualitatively operationalize the CBM objectives through our ongoing activities of surveying engineers, pilots, maintainers, and crew chiefs on the non-tangible and mission benefits of the VMEP system (safety, morale, mission capabilities, confidence on the system, and system liability).
- Combine the qualitative and quantitative measures from (1) and (2) above to validate that the VMEP system can meet CBM objectives. This task is particularly important in what is needed to develop a new paradigm shift for maintenance training. The combined measures will also be presented and evaluated mathematically, parametrically, and mechanistically as diagnosis models of components or systems. Such models will include and encapsulate, among other data collected, the flight regimes and flight profiles. A simulation model will be created to help the users practicing these tools virtually prior to implementations.
- The On-Board Vibrations Monitoring System (VMU) has been successful in identifying faults by the exceedance values of the Condition Indicators (CIs). Since the VMU systems are installed on existing aircraft, usage history and remaining life are still undetermined.

The goal of the test stand is to provide data and algorithms for usage and remaining life for new and existing parts. Components and parts that show excessive vibrations will be removed from the aircraft. These parts will be inspected and the fault will be recorded. The part will be placed in the test stand and run until final failure. When the CIs are fully refined and validated this sensor information will be integrated into the CBM framework that will be used to predict the overall health and the remaining life of components or systems.

• All collected data will have been interrogated and validated in the laboratory using our Helicopter Drive Component Test Stand. The test stand will be used to refine and improve our prognosis models by examining bearings, shafts and gears in order to correlate their conditions with the associated parameters both from new and existing components or operational aircrafts. Parameters to be monitored include, but are not limited to: wear, friction, oil condition, metals in oil, temperature, other tribological factors, vibration, condition indicators, and loading conditions and profiles.

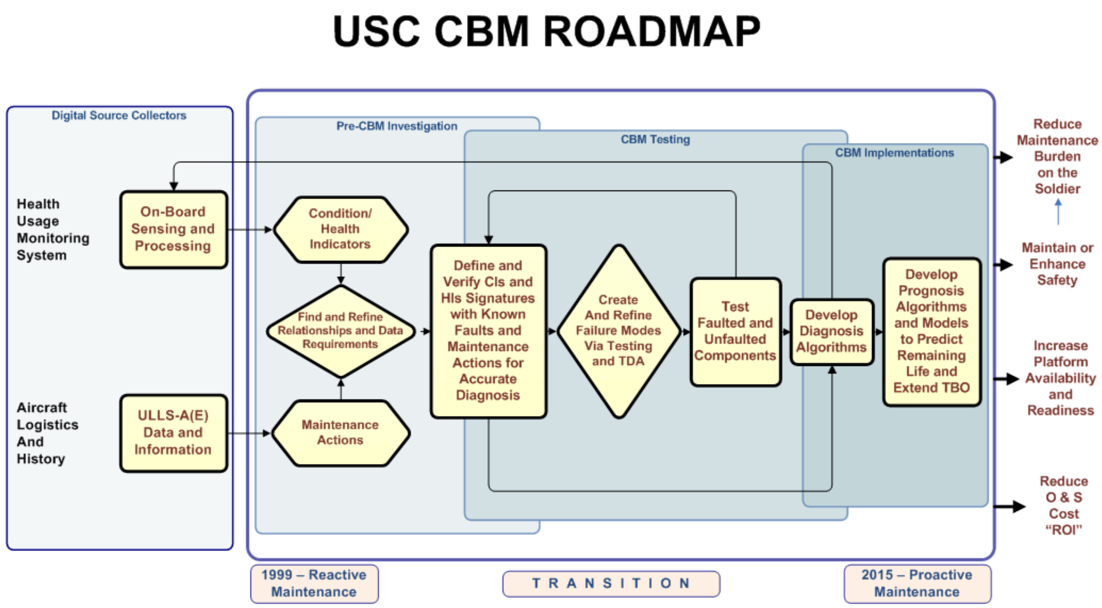

Figure 1--The procedural roadmap currently being implemented by the USC CBM research program

CBM Roadmap

As the growth and awareness of CBM develop, many ideas and technologies have arisen in efforts to improve CBM. Unfortunately without a plan or path, many of these ideas will never fully mature. There is need for a standardized methodology and roadmap for CBM to reach its full potential. In conjunction with the South Carolina Army National Guard, the University of South Carolina has the resources and channels to develop a roadmap to investigate the transformation of CBM. This can be done in a way that will address a broad array of strategic and tactical issues so as to accomplish the CBM specific objectives. The activities of USC are being performed as a joint industry, academic, and government team.

The roadmap consists of three phases: initial investigation, component and system testing, and the implementation of a fully-capable CBM system. This roadmap is driven by the currently available digital source collectors, which through integration and linking will direct the needs of laboratory testing. The results of this self-refining process will ultimately lead to the development of diagnosis and prognosis algorithms which will facilitate proactive CBM practices.

Creating a CBM Framework using Historical Data

A critical pre-requisite of CBM is to have a well established baseline of historical data by which to measure and compare performance, usage, wear and failure of helicopter performance. Our data on logistics, usage, maintenance, supply, mission, and training procedure provides a valuable building block in creating a baseline for CBM. This information is historical, accessible, and compatible with various electronic formats.

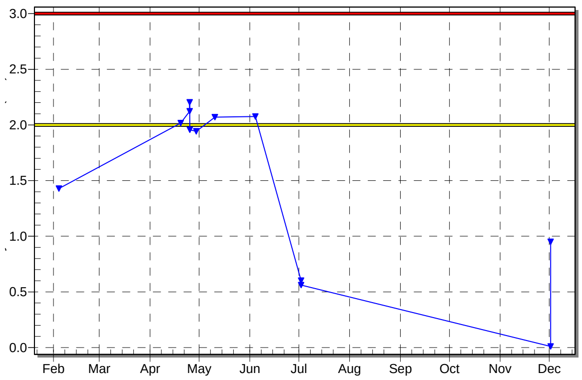

Figure 2 - Sample CI record as seen from GBS, the analysis tool provided with the MSPU. This particular case is showing a replaced hanger bearing that had failed a

The preliminary stage of a CBM investigation must begin with an examination of real world data. In the case of USC, this has occurred with the collection and analysis of Health and Usage Monitoring Systems (HUMS) data as well as Army maintenance logs, in the form of TAMMS-A or ULLS-A data, both of which play an equally important role in helping to define testing plans for specific components.

CBM team currently has access to a wealth of data collected by health and usage monitoring systems, particularly the **Modern Signal Processing Unit (MSPU)** and the **Vibration Management Unit (VMU).** The implementation of these systems requires the installation of several sensors at various points in the aircraft, and typically focuses on vibration levels of specific components during flight. The output of these sensors are collected and monitored by a central signal processing unit, where they are analyzed to determine a condition indicator for that region. Throughout the flight, these condition indicators are calculated and stored, creating a vehicle health profile that can be downloaded to a computer and examined to determine what maintenance actions are required.

The specific objectives of the implementation of these systems were to 1) reduce rotor track and balance maintenance test flights, 2) reduce aircraft operation costs, 3) increase aircraft availability, and 4) increase aircraft safety. The approach take was to 1) measure and record in-flight vibrations, 2) process vibration data, apply signal analysis methods, and identify "hot-spots," 3) fine-tune the track and balance of the aircraft to reduce vibrations, and 4) identify and address incipient failures through repair and/or replacements.

h Replacement Actions : Select Query

FAULT	ACTION
VMEP TAIL ROTOR MAG PICK-UP MOUNT BRACKET CORROADED	REPLACED T/R MAG P/U MOUNT BRACKET & INTERRU PTER
UHF ANT CONNECTOR DAMAGED BY VMEP REINSTALLATION.	REPLACED UHF ANT CONNECTOR @ RADIO.
VMEP CONNECTOR P1- #2 NGB DISCONNECT XMSN DECK AREA- STRAIN	REPLACED BACKSHELL
VMEP INDICATES #4 & #3 P/C/L OUT OF ADJUSTMENT	#4 & #3 P/C/L ADJUSTED AND REPLACED LOCKWIRE
VMEP INDICATES A CAUTION ON T/R AFT HANGER BEARING;IPS READING	REPLACED AFT HANGER BEARING S/N:2504
VMEP AFT H/B ACCEL #12 BROKEN.	REPLACED DURING PHASE, SEE PHASE FLIGHT PACK
T/R G/B SWASHPLATE VMEP MAG PICKUP REMOVED AND WIRE TEMP S	REPLACED MAG PICK-UP
VMEP NOT RECIVING A SIGNAL FROM MAG. PICK-UP.	REPLACED TACH #1
VMEP SENSOR #13 INOP	REPLACED
VMEP INDICATES DISPROPORTIONATELY HIGH VIBRATION FROM #2 T/R D	REPLACED #2 DRIVE SHAFT ASSY
OIL COOLER BAL. IPS W/I LIMITS. OIL COLLER BEARING VIBRATION LEVE	REPLACED OIL COOLER WITH SN# D512-01416.
OIL COOLER BAL IPS W/I LIMITS. OIL COOLER BEARING VIBRATION LEV	REPLACED OIL COOLER AXIAL FAN
OIL COOLER BAL IPS W/I LIMITS. OIL COOLER BEARING VIBRATION LEVEI	REPLACED OIL COOLER AXIAL FAN
VMEPS MAG PICKUP INOP DUE	REPLACED MAG PICKUP
BOLT MOUNTING THE VMEPS ON PTO CLUTCH SHEARED OFF	REPLACED PTO CLUTCH P308 WITH P510
AT 120 KTS, ENCOUNTERED LATERAL VIBRATION DECREASED AROUND '	REPLACED #1 M/R P/C/L
VMEP INDICATED FWD HANGER BEARING VIBRATION LEVELS INCREASIN	REPLACED HANGER BEARING WITH SN 2463
VMEP 5 AMP CIRCUIT BREAKER MOUNTED IN #1 PDP LOCATION D2 SHOU	REPLACED 5AMP CIRCUIT BREAKER MOUNTED IN #1 PDP LC
VMEPS SHOWS SOLID ERROR LIGHT AFTER SURVEY READING.	REPLACED M/R &T/R MAG PICK UPS
VMEPS FLAGS FWD HANGER BEARING WITH HAVING A HIGH VIBRATION	REPLACED FWD HANGER BEARING
VMEP SHOWS AFT HANGAR BEARING FAILURE	REPLACED AFT HANGAR BEARING SN 01183701767

Figure 3 - An excerpt of ULLSA data from USC's database showing a selection of VMEP related faults.

The **Unit Level Logistics Support – Aviation (ULLS-A)** system has been used to track parts and man-hour usage. The elements to be tracked include, but not restricted to 1) part S/N and cost, 2) man-hour for installation and troubleshooting, test-flight hours for confirmation or operational crew hours, identify if part is related or not to vibration (a tire – no; an on-board computer – yes; a hydraulic pump – maybe), and tear-down analysis results, when available. ("Might have operated another maintenance period" or "It is surprising that it lasted that long").

These records traditionally consist of hand-written log books which list every observation and action performed by maintenance crew personnel to a given aircraft.

As technology has progressed, the Army has moved much of these log books to a computerized form for easy storage and retrieval, allowing the entire history of a particular aircraft to be accessed within seconds. Since 1998, the CBM team at University of South Carolina has been collecting this type of maintenance records from various aircraft all over the world, creating a thorough baseline of historical data from which parameters such as logistical overhead and unit readiness can be evaluated. ULLS-A and vibration data were collected for Apache and Blackhawk aircrafts since 2000. In 2000, we started with 18 Apaches and 8 Blackhawks from the South Carolina Army National Guard (SCARNG). At present, we are collecting data for over 100 aircrafts (AH-64 and UH-60) from SCARNG, Alabama Army National Guard (ALARNG), Kosovo, Korea, and Iraq.

Data Collection and Analysis

Before relationships between maintenance actions and vibration data can be found, each component must be analyzed individually for greater accuracy and reliability. First, from the collected set of health and condition indicators, statistical analyses are performed to identify the central tendencies of each indicator for each aircraft type. Events that show a large deviation from the mean are identified as anomalies and are extracted for further analysis.

Maintenance Logs must be analyzed individually as well. Using a combination of Natural language processing as well as standard database organizational techniques, maintenance actions are categorized by their likelihood and severity.

Once a separate analysis on each data component has been performed, the finding of relationships between the two can be more easily found. Relationships between fault records and vibration data are collected from two separate directions. Based upon the aircraft tail number and incident date of high CIs, corresponding TAMMS-A records are extracted to find potential causes and/or effects of the event. When a potential match between the two data sets is found, it is used to direct the research efforts into examining components that will most likely produce results.

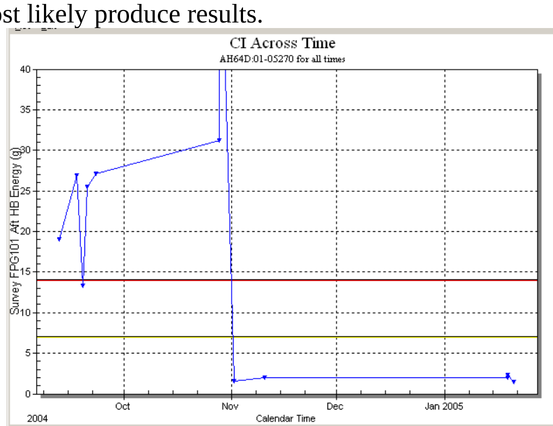

Figure 4 - The CI chart of a damaged MRSP bearing that required replacement.

Second, Maintenance actions are given associations with regard to their CI/HI level. Such maintenance actions are then pulled out individually for verification of their CI levels, and a trend analysis can be performed.

In addition to this, USC has taken the initiative to begin a direct correspondence with Maintenance crews from which data is being collected. This communication enables first-hand verification of relationships suggested by data.

This is a constantly refining process: relationship formation leads to experimental design test plans, the results of which can lead to an enhanced ability to identify more links between the data sets. The ultimate result of these first two objectives is a fully-integrated knowledge of the interactions of vehicle condition indicators and maintenance history.

This knowledge gives us the ability to assess the need to refine our data set. First and foremost, it allows us to quantify the accuracy and reliability of Condition/Health Indicators. Due to an increase in the knowledge of the part at the time of replacement, an assessment can be made as to the appropriate level that a condition indicator ought to be set.

In addition, the usefulness of specific components of ULLSA data can be more accurately assessed.

Once potential relationships between the two historical datasets have been found, those relationships are then backtracked in the attempt to quantify a time to action. Using a combination of flight hours as recorded in MSPU logs in addition to suggested inspection times from ULLSA records, an initial assessment about how long a part has been in place before a maintenance action is necessary. This knowledge gives our engineers the ability to assess which components most need to be tested, and allow for the development of test plans for replicating failure modes by using seeded faults.

Defining Failure Modes and Establishing Life Span Assessments

The preliminary relationships and status information derived from the combining of MSPU and ULLSA data are rough assessments based solely on what we believe to have occurred in flight, and are by no means exact. Through the use of USC's Seeded Fault test stand, these relationships can be improved and refined to make a more accurate statement regarding not only the condition of a component, but what is potentially wrong with it, and for how long it may continue to be used without a concern for failure.

Using the data retrieved from our historical data assessments, components showing the most likely production of propagation of failure are implemented on the test stand. In order to ensure accuracy and credibility, USC works with AED to seed faults into components, and run these parts to failure via pre-defined test plans. Periodically, components are removed and examined for fault propagation, at which time an analysis of changes in the component's vibration signature can also be assessed.

The vibration signature generated by these "seeded fault" parts that have a known defect can then be compared to predictions from historical data analysis, and more accurate assessments can be made.

For further verification, because the faults from these components is known, this information can also be used to confirm that the sensor generated data from the test stand matches faults that have been physically observed on actual aircraft. Using this information, the test stand gives us a more accurate estimate of time to failure, as these components were run on the test stand specifically for this purpose.

Once these tested components have been run to failure or near failure, a Teardown Analysis (TDA) can be performed. A TDA is a detailed examination of a failed component that attempts to identify the root causes of failure. The TDAs from our seeded fault components can then be compared to those from actual aircraft, and comparisons can be made.

Once a failure mode and a time to failure have been established, we can move on to creating a life span map for each component, which is the eventual end goal of USC's CBM process. Once a more accurate time to failure has been established for the majority of known faults, this information can then be used to show retroactively the present status of a component, and what maintenance actions will prevent this part from either failing prematurely, or having a negative effect on other components. These life span assessments can than be applied to a condition monitoring system used on live aircraft as a means of reducing maintenance actions, increasing operational availability, and improve the understanding of the underlying physics and root causes of component and system faults.

Cost Benefit Analysis of CBM: A Case Study of the VMEP Program

The Cost Benefits Analysis (CBA) has been executed in a 3-step procedure:

Define the CBA Objectives. The CBA focused initially on the AH-64 platform, and, after initial trials, were extended to include the UH-60 platforms. The investment efforts were focused mainly at the Unit-Level and below because the costs and benefits were most quantifiable at these levels.

Develop CBA Framework. The VM "building blocks" were considered as investment opportunities. The investment opportunities were analyzed in terms of primary and secondary benefits. For each presumed benefit, a definition and a metric were developed.

Cost Estimating and Benefits Analysis. The analysis initially targeted the operating and support (O&S) costs. The O&S costs are a subset of life cycle costs (LCC). We intended to address every aspect of O&S cost in search of major cost drivers. Pursuit of O&S cost reduction is particularly complex because problem areas and potential solutions involve multiple dependent variables. The O&S analysis were guided by the AMCOM document "Reduction of Operating and Support Costs for the US Army Helicopters" of 24 February 1995. In this activity, O&S estimates were developed, benefits were characterized, and impacts were organized. This activity had three levels of depth depending on assignment requirements. The analysis focused on selected VM "building blocks" that had the potential to show investment cost returns. Cost savings and cost avoidances from any source were considered as returns. A project would be successful if the benefits and returns exceed the investment cost. This factor was determined using return-on-investment (ROI) metrics, i.e., the ratio of savings to investment. Savings were represented by returns that are quantified in cost or financial terms.

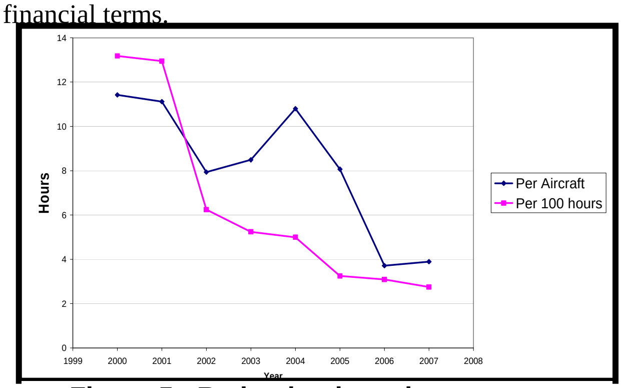

Figure 5 - Reduction in maintenance test flights for AH-64 and UH-60 helicopters at McEntire

One of the most demanding operations of active helicopters is **Maintenance Test Flights**, which are periodically used to determine if all elements of the helicopter are performing well. As time progresses, and the ability of maintenance crews to use the VMEP system has improved. Figure 4 shows the number of average number of flight hours for each aircraft at McEntire. The data was obtained from 2408-12 records, which contain flight logs for every aircraft. The blue line indicates the average number of hours on a per aircraft basis. Note the large spike in 2004. This is attributed to what we will call the "Deployment effect," whereby maintenance crews increase the number of flight hours as a means of ensuring complete success directly prior to a deployment, in this case Kosovo. To attempt to better account for this, flight hours were normalized per 100 flight hours, as indicated by the pink line. Note that there is no increase in 2004, as more flight hours in 2004 account for the increase in test flights. Based on the known cost of maintenance test flights, we can find the total annual cost reduction using the following formula:

$$TS_{MTF} = (FH_{Initial} - FH_{Final})*C_{MTF}$$

Where FH represents the number of Flight hours, and C represents the cost per hour. Based on the data collected, this equates to an average annual savings of **$15,196.88.** If we total this number for the duration of the data collection period (2000-2007), we can find that this is a per aircraft savings of **$121,575.00** over the 8 year period. **For a fleet of 18 aircraft, this becomes a total cost reduction of $2.2 million in maintenance test flights alone.**

The law of diminishing returns, however, would suggest that the VMEP system would in fact reach a new lower equilibrium number of MTFs after enough time. Based on the applied logarithmic regression model applied to the MTFs per 100 flight hours, we can project that this new baseline will be around 2.8 hours of maintenance test flights per 100 flight hours. This would indicate that **once the system reaches equilibrium, the annual savings would be $18,495.00 per aircraft.**

Another strong indicator of readiness is the **Reduction in Unscheduled Maintenance.** Maintenance actions, when recorded into log books (2408-13 records) are classified as either scheduled or unscheduled.

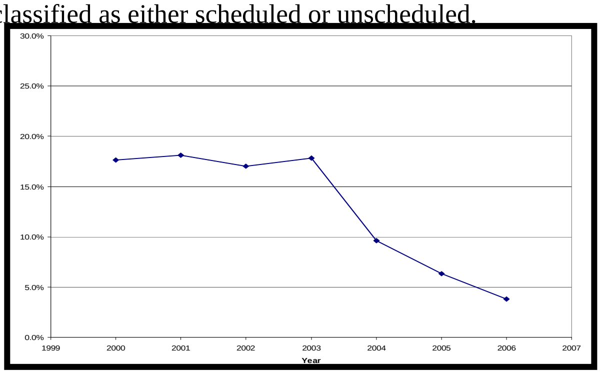

Figure 6 - Reduction in unscheduled maintenance as a percentage of total maintenance actions at McEntire.

Figure 5 shows the reduction in unscheduled maintenance over the data collection period, measured as a percentage of total maintenance actions. Data for 2007 was not present at the time of the study. There is a very clear reduction in unscheduled maintenance, aside from the spike in 2003, directly before a deployment to Iraq. At the conclusion of the study, **unscheduled replacements were reduced to less than 4% of total maintenance actions, and less that one fourth its baseline** pre-VMEP levels. This suggests that Maintenance Test Flights, in addition to the use of the VMEP system, are doing an increasingly better job of allowing maintenance crews more time to scheduled maintenance actions as indicated by the Ground Base Station (GBS).

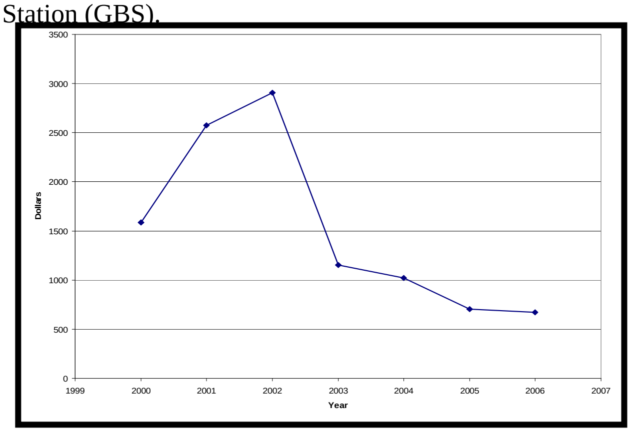

Figure 7 - Average annual parts cost per flight hour.

Measuring changes in **Parts Costs** produces mixed results, all of which can be accounted for. Initially, it is expected that the VMEP system, or any CBM system would create some increase in parts costs as maintenance crews replace some parts prematurely as indicated by the system. However, as the ability to use the system increases, parts costs will decrease, and eventually level off at a new lower equilibrium. This can clearly be seen in Figure 6, which shows the annual part replacement costs per flight hour at McEntire.

In the case of McEntire, **a new lower equilibrium would be expected to create an annual reduction of $75,000 from baseline levels.**

Measuring Non-Tangible Mission Benefits

Non-tangible benefits have been or will be analyzed in our model. These values are based on information and surveys from the base and are used to show the non-tangible benefits that arise from the use of VMEP. Again, the idea is that with the implementation of the VMEP program whether or not the fleet will see an increase in aircraft availability, safety, and operational flight hours along with a decrease in premature parts failure, mission aborts, and unscheduled maintenance occurrences.

Our original brainstorming sessions identified two categories of benefits, basic and mission, which are important areas to "measure" VMEP outcomes in a comprehensive cost and benefit model. Mission benefits, the "soft" benefit area, were conceived to comprise four areas: Operational Readiness, Morale, Performance, and Safety. We next committed to three steps through which our team would eventually be able to quantify and subsequently "measure" the non-tangible mission benefits achieved using the VMEP program.

Step 1. Our research team, crew chiefs, and pilots reviewed various iterations of a set of questions designed to address aspects of operational readiness, morale, performance and safety as they related to operating and maintaining Blackhawk and Apache helicopters. Numerous questions and items were suggested; and, through a series of review, discussion and reaction iterations, narrowed down to four items that addressed each of the four non-tangible mission benefit areas. Anchor points for each were created using a seven-point Likert` Scale.

Step 2. A questionnaire containing these sixteen items along with addition background questions was designed and pre-tested on a small group of crew members, crew chiefs, and helicopter pilots. Feedback about question wording and anchors was used to design a revised questionnaire. The revised questionnaire was pre-tested once again and a final, questionnaire created to use in surveying various units in the National Guard and

Regular Army that fly and maintain Blackhawk and Apache helicopters around the world.

Step 3. The questionnaire was administered to a SC National Guard unit at McEntire. The results were received and tabulated. The responses were used to check the questionnaire items' reliability and validity. Indicators of improvement in operational readiness, safety, morale and performance were noticeable. The results, as can be seen in a summarized form in the table below, suggested solid improvement in these mission benefit areas over the time since VMEP was introduced into this unit's aircraft.

Step 4. Our next step will be to conduct focus groups with crew chiefs, and focus groups with pilots, the purpose of which will be to identify quantifiable indicators associated with the Likert scale anchor points on each of the four questions across the four non-tangible mission benefit areas. The purpose of this step will be to engage people directly involved in using and maintaining these aircraft and most responsible for mission objectives to discuss and shape measurable indicators in areas like safety, operational readiness, morale and performance - what is the tangible payoff of higher morale, better safety, etc.

Step 5. Take the input from our focus groups, and with our research team and army advisory group agree upon measurable financial, time and other outcome "results" associated with Likert scale outcomes in the four non-tangible benefit areas. Our objective will be to quantify, financially whenever possible and credible, measures or multipliers we can apply to questionnaire answers in these areas. If we are not satisfied with the credibility and validity of the attempt to attach financial indicators, we will adopt a more academic research approach and create a "normalized" score for non-tangible benefits, much like the BCS creates a scoring system to rate football teams, and we will use it to "measure and quantify" in a meaningful way current and future responses to questions about non-tangible benefits.

- Safety – 16 % improvement
- Sense of Safety – 30% improvement
- Performance – 21% improvement
- Mission – 13% improvement
- Morale – 11% improvement
- Confidence – 20% improvement
- Morale– 35% improvement
- Ease of Troubleshooting – 32% improvement

Appendix A—Common Terms

Condition Based Maintenance:

Condition-Based Maintenance (CBM) is the nomenclature assigned to a maintenance process that is based upon the electronically determined condition of a component, sub-system or system.

Condition:

Condition is based upon electronic measurements that can be related to condition without the need to disassembly and inspect through conventional means.

General CBM Objectives:

- Reduce unscheduled maintenance and maintenance workload.
- Decrease maintenance and logistics footprints.
- Perform and integrate advanced engineering, maintenance, and information technologies.
- Maintenance only upon evidence of need.
- Improve diagnosis and prognosis capabilities.
- Use real-time assessments of material condition obtained from embedded sensors and/or external tests and measurements using portable equipment.
- Increase operational availability.

Condition Indicators (CI):

Condition indicator algorithms come in many varieties and capabilities. These condition indicators are in turn used to develop Health Indicators (HI).

Health Indicator (HI):

The Health Indicator (HI) is a non-dimensional metric that is constructed (calculated) by the manipulation of related condition indicators (the output of condition algorithms). The time history of a perfect HI would identically track (match) the time history of the CI.

Diagnosis:

Faults in bearings, gears and shafts can be detected. These detections are reported as magnitudes. Faulted shafts are the easiest to detect, and bearing faults are the most difficult.

Prognosis:

When it is possible to detect an increase in the magnitude of a detection algorithm output as a function of a tangible usage metric, it is possible to predict the useful service life remaining. This prediction is known as prognosis. A tangible usage metric is that usage metric that relates most directly to the loads and cycles causing the fault (or incipient fault) to propagate. In the case of a helicopter power train, there are many potential metrics:

- Flight time
- Operating time (running time)
- Power spectrum
- Time integral of applied power (throughput power)
- Time integral of applied power normalized for the system S-N Characteristic (Normalized Throughput Power.)

Usage of Mechanical Systems:

Usage is defined as time integral of the power applied to the mechanical system. This usage is also known as generic system usage.

Flight Profile:

A flight profile is a series of ground and flight phases (or events). The simulation program is limited to the simulation of mechanical power train health during flight operations and ground operations when the rotor is turning. The analyst (user) will be able to create flight profiles or use an existing flight profiles. For the purposes of this simulation, the program needs to know the sequence of the various phases and the time spent in each phase.

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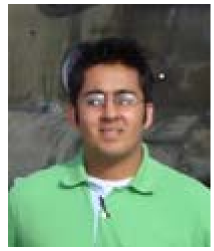
25. Unfunded Mandates CG, AMCOM Sets Initial Operating Capability Objectives FY 2011
26. Unfunded Mandates - DA, G4 – Army CBM Plus Memorandum Sets Plans for Implementation Dtd: 08-17-05

Appendix B—Biographies

Abdel-Moez E. Bayoumi, Ph.D., has over 25 years teaching and research experience. Dr. Bayoumi is Director of the Condition-Based Maintenance Center, Director of the Biomedical Engineering and Professor of Mechanical Engineering at the University of South Carolina College of Engineering and Computing. Before joining USC, he was a Professor of Mechanical and Aerospace Engineering at North Carolina State University, a project manager at Hewlett-Packard Company, and Professor of Mechanical and Materials Engineering at Washington State University. He has been actively involved in developing strong programs in mechanical systems. His research activities have been focused in mechanical behavior of materials and design, diagnosis and prognosis of mechanical systems, and design for manufacturability. He has published over 100 papers and supervised fourteen doctoral and thirty-five masters' students.

General Lester D. Eisner is currently serving as the Deputy Adjutant General, South Carolina Army National Guard. He was commissioned into the U.S. Army in 1976. BG Eisner has held key various staff and command positions including battalion and brigade command. He has logged over 5000 hours in various U.S. Army fixed and rotary winged aircraft, including the UH-60 and AH-64. He is a graduate of the U.S. Army War College. BG Eisner has provided key leadership for many years in the development of embedded diagnostics technology for the U.S. Army helicopter fleet. He served as the Director of the Vibration Management Enhancement Program.

Chief Warrant Officer Five Lemuell Grant graduated from Georgia State University with a BS in Criminal Justice. He served over 40 years as an Army Aviator, Instructor Pilot and Maintenance Test Flight Examiner. During his career, he was twice awarded The Distinguished Flying Cross, fifty-six Air Medals and the Broken Wing Award. He was instrumental in the development of the Army Vibration Analyzer (AVA) and the Vibration Management Enhancement Program (VMEP). He continues to work in the field of Conditioned Based Maintenance.



Ronak Shah received his B.S. degree in Economics from the Moore School of Business at USC in May 2007 specializing in Applied Microeconomics with a minor in Computer Science with a focus on Database design and development. Throughout his college career, he has been involved in a number of open source projects through the Open Source Developers Network, and has developed a programming background and skills in web applications development and content management. Ronak is currently working on a M.A. in Economics at USC while working with the Condition-Based Maintenance center in conjunction with the US Army on Cost-Benefit Analysis modeling for CBM objectives.

Nicholas Goodman received his B.S. degree in Mechanical Engineering in May 2006 with a minor in Mathematics and Computer Science, specializing in Artificial Intelligence. Following a six month language study trip to East Asia, he began working towards a M.S. in Mechanical Engineering, with a specialization in Mathematics. Nicholas is also a seasoned programmer who has significant experience in working with control systems and software development. He is currently investigating the development of neural network algorithms for the analysis of rotorcraft vibrations and maintenance data in support of CBM objectives for the U.S. Army.

Dr. John Keller received his B.S. (1995) in Aerospace Engineering from Penn State University. He went on to receive his M.S. (1997) and Ph.D. (2001) in Aerospace Engineering from Penn State University, with a Fellowship from the Rotorcraft Center of Excellence. Dr. Keller has been an Aerospace Engineer with the Aeromechanics Division of the Aviation Engineering Directorate since 2001.