Army Aviation's Unrealized Potential

A Monograph

by

MAJ James R. Carroll
US Army

School of Advanced Military Studies
US Army Command and General Staff College
Fort Leavenworth, KS

2018

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
03/01/2018

2. REPORT TYPE
Master's Thesis

3. DATES COVERED *(From - To)*
JUN 2017 - MAY 2018

4. TITLE AND SUBTITLE
Army Aviation's Unrealized Potential

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Maj. James R. Carroll

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Command and General Staff College
ATTN: ATZL-SWD-GD
Fort Leavenworth, KS 66027-2301

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Advanced Military Studies Program, School of Advanced Military Studies.

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Readiness is the number one priority of the US Army, but cost increases and budgetary turbulence make that goal more difficult each passing year. Army Aviation, the service's most expensive branch, will spend over three times as much maintaining its current aircraft as it cost to purchase them. With increased budget unlikely, but increased mission complexity certain, the primary means to achieve readiness in Army Aviation is reducing the cost of operating and maintaining its fleet. Other aviation organizations, in and out of the Department of Defense, addressed similar challenges successfully by continually refining maintenance processes to a degree that the Army has not.

15. SUBJECT TERMS
Army Aviation; Aviation Maintenance; Maintenance Management; Condition Based Maintenance; Condition Based Maintenance Plus, Maintenance Steering Group; MSG-3; Reliability Centered Maintenance; RCM; Readiness

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Maj. James Carroll
					19b. TELEPHONE NUMBER *(Include area code)*
(U)	(U)	(U)	(U)	45	714 726 7433

Monograph Approval Page

Name of Candidate: MAJ James R. Carroll

Monograph Title: Army Aviation's Unrealized Potential

Approved by:

__________________________________, Monograph Director
Dan C. Fullerton, PhD

__________________________________, Seminar Leader
Jason A. Curl, COL

___________________________________, Director, School of Advanced Military Studies
James C. Markert, COL

Accepted this 24th day of May 2018 by:

___________________________________, Director, Graduate Degree Programs
Robert F. Baumann, PhD

The opinions and conclusions expressed herein are those of the student author and do not necessarily represent the views of the US Army Command and General Staff College or any other government agency. (References to this study should include the foregoing statement.)

Abstract

Army Aviation's Unrealized Potential: a monograph at the School of Advanced Military Studies, by MAJ James R. Carroll, USA, 45 pages.

Readiness is the number one priority of the US Army, but cost increases and budgetary turbulence make that goal more difficult each passing year. Army Aviation, the service's most expensive branch, will spend over three times as much maintaining its current aircraft as it cost to purchase them. With an increased budget unlikely, but increased mission complexity certain, the primary means to achieve readiness in Army Aviation is reducing the cost of operating and maintaining its fleet.

Other aviation organizations, in and out of the Department of Defense, addressed similar challenges successfully by continually refining maintenance processes to a degree that the Army has not. This study examines multiple such cases to determine whether significant gains for an existing aircraft fleet are possible. Next evaluated is the potential for Army Aviation's current equipment and practices to benefit from such revisions. The resulting answer is that unrealized maintenance efficiency exists in the aviation force today and may represent the best path toward the readiness demanded by current and future Army missions

Contents

Acknowledgements

I am forever indebted to the love of my life Courtney Justice, whose unending grace and patience through this adventure made it possible. Additional gratitude belongs to the rest of our family, who have consistently shouldered a burden in my absence. I would also recognize the help of COL Richard Martin, whose experience and research in the field were a needed anchor to my own.

Acronyms

AAESS	Army Aviation Enterprise Sustainment Strategy
ADP	Army Doctrine Publication
AMCOM	Aviation and Missile Command
AR	Army Regulation
CAB	Combat Aviation Brigade
CBM	Condition Based Maintenance
CCAD	Corpus Christi Army Depot
DA	Department of the Army
DoD	Department of Defense
DOTMLPF-P	Doctrine, Organization, Training, Materiel, Leadership, and Education, Personnel, Facilities, and Policy
FMC	Fully Mission Capable
FY	Fiscal Year
HVM	High Velocity Maintenance
LTG	Lieutenant General
MG	Major General
MSG	Maintenance Steering Group
NMC	Non-Mission Capable
RCM	Reliability Centered Maintenance
TM	Technical Manual
TRADOC	Training and Doctrine Command
TB	Technical Bulletin
USAF	United States Air Force
USMC	United States Marine Corps

Tables

Introduction

The US Army increasingly relies on its Aviation branch to support a diverse array of global missions requiring a vertical maneuver or support capability. The Department of Defense (DoD) Fiscal Year (FY) 2017-2046 Annual Aviation Inventory and Funding Plan projects a significant increase in only one category of manned aircraft, attack helicopters, throughout its ten-year inventory analysis. The Army currently operates seventy-eight percent of the airframes in that category, and projects that number growing to eighty-one percent by FY 2026. It similarly retains the largest portion of airlift, cargo, and utility aircraft, at sixty-seven percent of the DoD's inventory, throughout the projected period.[1] Accordingly, Aviation programs consume the largest portion of the Army's procurement and modernization budgets, and the high cost of sustaining aircraft contributes significantly to the Army's $45.2 billion annual operations and maintenance budget.[2]

Immediately upon assuming office, Chief of Staff of the Army General Mark A. Milley communicated his service's number one priority as readiness. Readiness, in this case, means the ability to accomplish the Army's assigned missions, with sufficient training and resources to ensure their success.[3] Army Aviation shares that priority but struggles to meet its demands in the face of increasing mission complexity and budgetary limitations. As the Army's ability to accomplish complex missions increasingly relies on its helicopters, aviation readiness has the potential to directly impact Army readiness.

[1] US Department of Defense, *Annual Aviation Inventory and Funding Plan Fiscal Years 2017-2046* (Washington, DC: March 2016), 5.

[2] Thomas A. Hornlander, *Army FY 2017 Budget Overview* (Washington, DC: Department of the Army, 2016), accessed December 3, 2017, http://www.defenseinnovationmarketplace.mil/resources/Army%20FY%202017%20Budget%20Overview.pdf.

[3] Department of the Army, *39th Chief of Staff of the Army Initial Message to the Army*, by GEN Mark A. Milley (Washington, DC: September 2015).

Major General (MG) William Gayler, current Commanding General of the US Army Aviation Center of Excellence, delivered remarks to Congress in November 2017 that highlighted the branch's readiness challenges. MG Gayler reaffirmed that the Army Aviation branch's number one priority, in support of the Army's same number one priority, is readiness. The address noted that hours flown by Army aircraft during fiscal year 2017 were "among the lowest" of any one-year period since 1987, owing to a complex array of mission requirements and funding changes. MG Gayler additionally detailed the Aviation branch's efforts to increase warrant officer strength in response to a potential pilot shortfall. The current funding level for Army Aviation enables 10.8 flight hours per month, per aircrew, which is sufficient to maintain proficiency at platoon-level tasks.[4] In other words, the Army intends to increase the number of pilots it has, while its missions reduce the overall number of hours flown, with funding insufficient to conduct training at the company and battalion levels it says are necessary for Unified Land Operations.[5]

Other aviation organizations, inside and outside of the DoD, successfully tackle similar challenges by reducing the operation and sustainment cost of their aircraft fleets. These organizations produce aircraft availability, which enables mission readiness, at improved dollar efficiency because their maintenance practices evolved to keep pace with their readiness requirements. Various Army and Aviation branch strategies implore the force to modernize these practices, but manufacturer and regulatory procedures which define them have not significantly changed in response to this guidance. Current Army Aviation maintenance practices waste critical readiness that other organizations realize by better-utilizing the same capabilities the Army

[4] House Armed Services Committee Subcommittee on Readiness, Statement by MG William K. Gayler, 115th Cong., 1st sess., 2017, 2, 5-8.

[5] Unified Land Operations, defined in Army Doctrine Publication 3-0, is the Army's term for its fundamental operational doctrine. Proficiency in Unified Land Operations implies that a combat unit can combine offensive tasks, defensive tasks, stability tasks, and defense support of civil authorities in conjunction with joint, interagency, intergovernmental, and multinational partners. A unit which is capable of coping with this complex array of tasks against peer or near-peer competitors must be trained extensively at higher levels than were necessary for aviation support during the Global War on Terror.

currently possesses. Aviation organizations with modern maintenance practices offer a model for exploiting Army Aviation's unrealized potential readiness.

Methodology

Army Aviation has an imperative to change its maintenance practices because the current approach leaves unrealized readiness, safety, and dollars on the table. Revealing this requires reviewing key maintenance concepts which provide a language to navigate current Army maintenance policies and understand how they bind maintenance procedures in stasis. The relevant human factors affecting aviation maintenance are additionally reviewed, demonstrating that current Army maintenance practices lack resilience against poor judgment and performance, and that contemporary Aviation missions exacerbate this quality.

Three brief studies will examine what maintenance advancements are possible for the Army. The first presents examples of aviation maintenance evolution outside of the Army, both in and out of the Department of Defense, to show how other organizations have procedurally evolved beyond current Army practice. The second demonstrates that the technological systems already operating on Army rotorcraft have the potential to facilitate such procedural evolution. Finally, a review of current Army and Aviation strategies shows that while the Army is conceptually in favor of such evolution, the commitment necessary to achieve such change is not yet present.

The Imperative for Change

Army aircraft are complicated, expensive systems whose safe use necessitates similarly complicated and expensive sustainment requirements. As an example, the AH-64D Apache Longbow helicopter's annual operating and maintenance cost to the Army is about $3.1 million per aircraft in 2010 dollars.[6] Given a nearly thirty-year planned service life for AH-64D aircraft, the total spent on flying and maintaining far outweighs the initial purchase price of each airframe. To evaluate the potential for improving such high maintenance costs, the underlying concepts, maintenance policies, and relevant human factors require review.

Key Maintenance Concepts

Every type of aircraft, civil or military, is maintained within a meticulous program of government and manufacturer specified inspections and overhauls. Several maintenance philosophies inform the design of maintenance programs, and multiple philosophies are routinely integrated into the same aircraft. The resulting program, known as a maintenance regime, varies between different aircraft types and models, though with similar goals including: safe operation, maximum flying availability, and lowest cost. Each philosophy addresses the tension inherent in these goals differently, so regimes commonly incorporate aspects of multiple philosophies.

Preventative maintenance is a maintenance philosophy based on systematic inspections and actions designed to retain equipment in a specified condition.[7] The goal of preventative maintenance is to prevent incipient failure of Army equipment by performing these inspections or actions prior to such failure occurring.[8] The dominant maintenance philosophy within Army aviation is a preventative regime of scheduled inspections based on flying hours, calendar days, or both. The phase maintenance inspection, the largest of the scheduled inspections, defines a series of increasingly detailed maintenance actions performed based on individual aircraft flight

[6] Department of Defense, *Selected Acquisition Report (SAR) AH-64E Apache Remanufacture* (Washington, DC: 2015), 36-37.

[7] The term “preventative maintenance” is used interchangeably with “preventive maintenance” depending on the source document and organization.

[8] Department of the Army, *Pamphlet (PAM) 750-8 The Army Maintenance Management System (TAMMS) Users Manual (*Washington, DC: US Government Printing Office, 2005), 309.

hours. Each airframe type has a peculiar inspection regime, but they are all fundamentally preventative, and driven by the phase maintenance scheduled inspection system.

Condition Based Maintenance (CBM) is an equipment maintenance strategy that enables proactive maintenance decisions by using system health monitoring technologies to predict system failures. An example of such a decision enabled by CBM is the replacement of an AH-64D Apache helicopter drivetrain component whose impending failure is detected before its scheduled maintenance interval. Continual vibration measurement and analysis by the on-board data collection system alerts the maintainers that this component's performance has trended away from an ideal baseline and is approaching a threshold beyond which failure is imminent. Unit maintenance managers can justify replacing the component ahead of its scheduled interval because of the current system condition knowledge provided by the CBM system. Such systems are currently installed across the Army manned helicopter fleet and are primarily designed to monitor the health of rotating drivetrain components. Aviation units routinely transfer CBM flight data to the Army Aviation and Missile Command (AMCOM) CBM Data Warehouse.[9]

Predictive maintenance is a philosophy resulting from improved technology and the desire to improve the maintenance efficiency of complex, heterogeneous systems. Diagnostic technologies, such as the sensors enabling CBM currently installed on many Army aircraft, allow maintenance managers to gain an accurate picture of the current condition of an aircraft component without performing intrusive physical inspections. Predictive systems express the condition of a given component, or a system of components, by mapping the elements of the system, their relationships, and the effects of potential faults at each point to determine a current state of function. Prognostic technology builds on diagnostic information, to estimate the remaining time to failure of a component based on its current state. These capabilities enable

[9] US Army Aviation Center of Excellence, *Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy* (Fort Rucker, AL: 2016), 4-6.

predictive maintenance decisions, which allow maintenance managers to gain the maximum lifespan out of aircraft components, with the greatest possible safety, at the lowest maintenance cost.

Condition Based Maintenance Plus (CBM+) is a Department of Defense (DoD) initiative directing each service to implement weapons systems maintenance and logistics support programs that incorporate tenets such as: minimum necessary maintenance, need-driven maintenance, embedded diagnostic and prognostic systems, and smaller maintenance and logistics footprints. The objective of CBM+ is to improve the reliability and availability of weapons systems while reducing life cycle costs. The CBM+ strategy identifies weapons system maintenance as a major portion of total system cost. The impacts of unnecessary maintenance include higher life cycle costs and reduced availability per system. The CBM+ initiative thus establishes an imperative for each service to exploit existing and emerging maintenance technologies, such as CBM systems, to perform maintenance based on "evidence of need." [10]

Reliability Centered Maintenance (RCM) is the process by which manufacturers and the Army establish maintenance regimes for weapons systems and equipment including aircraft. Through RCM they identify every possible failure mode in a new system, develop procedures to maintain the system, and continuously optimize those procedures once they field the system and new information or systems become available. This philosophy emerged from the civilian airline industry, and the Army mandates its use for developing materiel maintenance regimes.[11] RCM specifically focuses on achieving two objectives in developing a maintenance regime: cost effectiveness and reducing the probability of failure. To those ends, an RCM-derived

---

[10] Department of Defense, *Memorandum for Secretaries of the Military Departments: Condition Based Maintenance Plus* (Washington, DC: Department of Defense, 2002).

[11] Department of the Army, *Army Regulation (AR) 750-1 Army Materiel Maintenance Policy* (Washington, DC, 2017), 90-91.

maintenance process ideally includes the optimal balance of CBM actions, preventative actions, fault finding, and run-to-failure maintenance techniques.[12]

Army aircraft are maintained primarily within the scheduled phase maintenance inspection, a preventative maintenance regime which focuses on maintaining the condition of equipment in a desired condition. Though currently fielded aircraft utilize predictive technologies, such as CBM, to realize improvements in safety and efficiency, these technologies have not changed the philosophy under which Army Aviation conducts maintenance. Both CBM+ and Army Regulations promote evolving maintenance practices toward an RCM-derived regime by leveraging emerging technologies. An ideal weapon system maintenance strategy for the Army, then, would be one developed through the RCM process, incorporating multiple maintenance philosophies, which reduces maintenance costs and increases system availability while complying with the requirements of CBM+.

Army Aviation Maintenance Policies

Army Regulations, Department of the Army Pamphlets, and Technical Manuals detail Army Aviation maintenance policies and general procedures. Aircraft-specific procedures vary across different airframes and manufacturers, but all common practices described in those documents govern all Army Aviation maintenance. The three defining topics are materiel maintenance, maintenance management, and readiness reporting.

Army Regulation 750-1 *Army Materiel Maintenance Policy* communicates DA policies for a variety of maintenance categories including CBM and RCM. This document recognizes that CBM is not appropriate for all failure modes in all equipment, and therefore notes that no maintenance approach can rely solely upon CBM technology. AR 750-1 importantly clarifies that

[12] US Army Aviation Center of Excellence, *Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy* (Fort Rucker, AL: 2016), 4.

the purpose of RCM is not to prevent failure, but to manage the consequences of failure in a system or component while striving to preserve desired functionality. Additionally, it mandates that the maintenance strategies utilize the RCM process to integrate CBM, and notes that RCM requires continuous updates throughout a product life cycle.[13]

Technical Manual (TM) 1-1500-328-23 *Aeronautical Equipment Maintenance Management Procedures* outlines general procedures for managing inspection requirements of Army aircraft using a preventative maintenance framework. It defines processes that apply to all Army aviation systems, subsystems, and ancillary equipment. These processes, including the phase maintenance inspection system, represent the bulk of scheduled maintenance performed on Army aircraft. While Army Regulations or manufacturer maintenance instructions can override the general framework established in TM 1-1500-328-23, current Army aircraft maintenance programs comply with its preventative regime. While AR 750-1 mandates RCM as a process to create maintenance regimes for Army equipment, the Army's maintenance regimes have not embraced its continually evolving, iterative nature. This manual does not mention or incorporate preventative maintenance technologies or philosophies, nor does it address the risk or cost inherent to performing unnecessary maintenance actions.[14]

The complicated nature of Army aircraft is evident in the structures erected to support them. Each flying battalion possesses its own Aviation Maintenance Company, with over 100 soldiers from several specialties performing scheduled maintenance on between twenty and thirty helicopters. One Aviation Support Company further bolsters each Combat Aviation Brigade (CAB), applying hundreds of additional maintainers toward the same primary objective of aircraft

---

[13] Department of the Army, *Army Regulation (AR) 750-1 Army Materiel Maintenance Policy*, 94-95.

[14] Department of the Army, *Technical Manual 1-1500-328-23 Aeronautical Equipment Maintenance Management Procedures* (Washington, DC: 2014), 2-1 through 2-3.

readiness.[15] Army Regulation 700-138, *Army Logistics Readiness and Sustainability*, defines Army aircraft readiness objectives for maintenance managers. The term Fully Mission Capable (FMC) describes an aircraft able to "perform all of its combat missions without endangering the lives of crew or operators," further noting that the equipment must be on hand in the unit to qualify. An equipment readiness rate, expressed as a percentage, is determined by dividing the number of days each aircraft is FMC by the number of days within the reporting period and multiplying by 100. The Army's standard for aircraft readiness is seventy-five percent available. Put another way, each aircraft in a flying unit should be FMC for over twenty-two days of a thirty-day month.

Readiness reporting and goals incentivize units to be efficient stewards of government resources, while preventative maintenance programs ensure minimum safety standards exist for equipment operators. These two motivations are often discordant, and the management imperative to swiftly return a Non-Mission Capable (NMC) aircraft to service occasionally results in shortcuts or errors which can damage aircraft. An extensive preventative maintenance schedule, like those the Army currently uses, mandates that maintainers fit all scheduled and unscheduled maintenance activities into the remaining eight days of that thirty-day month if they hope to attain the seventy-five percent FMC goal.[16] As with every Army unit, the current manpower strength of an Aviation Maintenance or Support Company erodes rapidly against training requirements, schools, and leave, but the need to meet readiness goals is rarely absent. AR 700-138 tacitly acknowledges the challenges inherent to aviation maintenance by noting that

[15] Department of the Army, *Army Regulation 700-138 Army Logistics Readiness and Sustainability* (Washington, DC: 2004), 22.

[16] Army aviation units strive for the seventy-five percent availability goal across their aircraft during a specific reporting period. While the example of eight days of downtime out of thirty available would produce a seventy-five percent FMC rate for those thirty days, it does not imply that those eight days are contiguous, or that all aircraft in the unit would be down simultaneously. Maintenance managers balance scheduled maintenance requirements to maximize available aircraft for each reporting period based on the anticipated mission requirements and other factors.

every Army system, except for aircraft, has an FMC goal of ninety percent. Despite this, the dual goals of readiness and safety manifest tension within aviation maintenance organizations.

Human Factors in Aviation

Any maintenance action that does not fix a fault harms both readiness and safety; the aircraft is not FMC while it is being serviced, and all maintenance exposes the aircraft's systems to human error. Kara A. Latorella and Prasad V. Prabhu, in "A Review of Human Error in Aviation Maintenance and Inspection," examined the factors associated with human error in civil aviation maintenance which experiences a similar tension between availability and safety. Importantly, they identify that human maintainers have "failure rates and tolerances analogous to hardware/software elements of a system." The burden, then, is on maintenance system designers to incorporate and account for human performance to the greatest extent possible, rather than allowing the outcome of the maintenance to drive one's view of human performance.[17] A maintenance system which presents humans unnecessary opportunities to underperform, such as one that removes and replaces working components, invites unnecessary risk.

Army aviation maintenance practices account for human error by rote action, extensive documentation, and an independent quality control function which inspects all work maintainers perform. These organizational peculiarities are good and necessary, but do not eliminate human failure rates inherent in all aircraft maintenance actions. Aviation accidents attributable to failures in materiel decreased faster than those attributable to human error between 1960 and 2000, indicating that efforts to improve machine performance were more effective than those to improve human performance.[18] Airline operators, as an example, have made and are still making

[17] Kara A. Latorella and Prassad V. Prabhu, "A Review of Human Error in Aviation Maintenance and Inspection," *International Journal of Industrial Ergonomics*, no. 26, (2000), 133-161.

[18] Federal Aviation Administration, *A Human Error Analysis of Commercial Aviation Accidents Using the Human Factors Analysis and Classification System (HFACS)* (Washington, DC: 2001), 1.

great strides in evolving their maintenance systems by designing them to reduce opportunities for human maintainers to commit errors.

The Federal Aviation Administration's (FAA) *Human Factors Guide for Aviation Maintenance* places maintainer errors into three categories: slips, or errors of performance; mistakes, or errors of planning; and violations, generally described as shortcuts. It cites the top three causes of 120 in-flight engine shutdowns on Boeing 747 aircraft as missing parts, incorrect parts, and incorrect installation of parts. It also reports the dominant discrepancy types within 122 maintenance failures detected by a major airline as omissions, incorrect installations, and wrong parts. Aviation maintenance is a complicated industry, using detailed regulations to govern all maintainer actions, yet less than adequate human performance remains a primary factor in aviation safety.[19]

From this perspective, any preventative maintenance action performed on an FMC aircraft that does not correct an equipment fault actively works against the regulatory imperatives to be efficient and safe. Any time a maintainer opens a panel, or removes a component, it exposes the aircraft to the possibility for human error. In aviation, even something as easy as leaving a small tool behind can produce catastrophic results. Detailed records-keeping, the bedrock practice of safe aviation maintenance, exposes aircraft to the same risk of errors because the record is what proves the aircraft is safe, and all maintenance modifies the record.[20] A maintenance system focused on component reliability above system reliability thus increases opportunities for errors. High maintainer proficiency is a way to counter this risk, but that proficiency is susceptible to the same erosion of human performance that occurs in any of the difficult mission settings the Army may require. Because maintainers perform many inspections on a preventative basis, they

[19] Federal Aviation Administration, *Human Factors Guide for Aviation Maintenance* (Washington, DC, 2014), 3-6.

[20] US Department of the Army, *Army Tactics, Techniques, and Procedures (ATTP) 3-04.7 Army Aviation Maintenance* (Washington, DC: Government Printing Office, 2017), 5-8.

routinely dismantle, inspect, and reinstall many working aircraft. The intent of the inspection is to improve the safety of the aircraft by detecting the failure of the component, but if the component has not actually failed then the act only served to expose the aircraft to potential maintenance mistakes. Therefore, a maintenance system which provides unnecessary opportunities for human failures to affect safety invites unnecessary risk to aircrews, aircraft, and their missions.

Lieutenant General (LTG) Kevin Mangum, speaking to the House Armed Services Committee's Subcommittee on Readiness in 2016, cited maintenance readiness, maintenance manpower, and human error as three of the largest obstacles for Army Aviation. Branch-wide FMC rates fell short of the Army's seventy-five percent availability goal between 2001 and 2016. Personnel caps for deploying units created a reliance on contractor-supported maintenance in deployed environments, and left Army aircraft maintainers with reduced technical experience. Shallow organic maintenance experience means soldiers work on aircraft with a reduced capacity for technical troubleshooting and task management, so maintenance takes longer. Longer maintenance intervals mean fewer available aircraft, limiting the potential for aircrew and unit training by increasing the cost of each flight hour. Reduced aircrew proficiency increases the potential for human error, a contributing factor in eighty percent of all Army Aviation accidents.[21]

Ample evidence of the combined effects of reduced proficiency and human error resides in the pages of the Aviation branch safety magazine *Flightfax*. The May, 2012 issue of *Flightfax* documents an AH-64 incident in Afghanistan where the intersection of maintainer and aircrew proficiency, human error, and current maintenance procedures created a disastrous outcome.[22]

---

[21] House Armed Services Committee Subcommittee on Readiness, Statement by LTG Kevin W. Mangum, 114th Cong., 2nd sess., 2016, 5-8.

[22] "Flightfax Online Report of Army Aircraft Mishaps," US Army Combat Readiness Center, accessed November 17, 2017, https://safety.army.mil/Portals/0/Documents/ON-DUTY/AVIATION/FLIGHTFAX/Standard/2012/May_2012_Flightfax.pdf.

One week prior to the incident, a maintainer replaced a flight critical tail rotor drive component without properly torqueing its bolts. This incipient failure remained because the bolts appeared correct to the naked eye, and because the supervisor erroneously signed off maintenance records as correct. During a ground test, the onboard CBM system recorded increased vibration in the faulty component, but because maintenance procedures only required someone to examine the data in detail every fourteen days (or twenty-five flight hours) it prompted no further inspection.[23]

A mission crew, in that aircraft, launched to support US troops under enemy contact, but were forced to land when the CBM system detected vibrations above a safety threshold and displayed a cockpit warning. After the warning extinguished, they performed incorrect troubleshooting and decided to fly the aircraft back to a maintenance facility for further inspection. One minute into the return flight, the CBM system again alerted them to the fault, they failed to execute the emergency procedure it required, and several minutes later the component failed resulting in a crash. Low maintainer proficiency created an incipient failure with which maintenance procedures and less proficient aircrews failed to cope. The troops in contact with enemy forces did not receive the air support they required, the crash site needed ground security and resources, the theater was robbed of an extremely valuable attack helicopter, the aircrew remained unavailable to fly missions until the crash investigation concluded, and that investigation consumed additional pilots necessary to investigate. Aviation maintainers, aircrew, and the maintenance regime should combine to reduce the risk of human underperformance, not amplify it.

Army Aviation's ability to generate readiness is not currently limited by spare parts, special tools, or key facilities, but by low maintainer proficiency and the high costs of current

[23] Ibid.

maintenance regimes.[24] As a comparison, Southwest Airlines' passenger jet maintenance system requires eighty-two days of scheduled down time during a thirty-year Boeing B737 aircraft lifespan. Each Southwest aircraft suffers fewer than three days of scheduled maintenance downtime per year, leading to a fleet readiness rate of 99.97% availability.[25] Even if Army Aviation was meeting its readiness goal of seventy-five percent, the largest helicopter fleet in the world would still be almost twenty-five percent worse at making use of its aircraft. Army Aviation maintenance processes have not kept cost or availability pace with those in other organizations, and this lag is exaggerated by complex mission requirements. Budget and force cap limitations reduce maintainer proficiency, which reduces aircraft readiness, which reduces training availability to crews and mission availability to customers, increasing the expense of operations and sustainment, which further pressures the budget. The Army can break this cycle, or exploit it to positive effect, by a systemic change to Aviation maintenance which leverages the RCM advancements made in other organizations.

RCM Outside the Army

Though the military generally embraces advances in aviation technology, the airline industry provides the state of the art in aircraft maintenance regimes. Pressured to similar goals by different forces than is Army Aviation, airline operators currently benefit from a fifty-year organized effort to continually improve maintenance processes. Military aviation fleets, by comparison, tend toward process stagnation as aircraft lifespans exceed original intentions and modernization efforts focus on next generation acquisitions.[26] The evolution of these processes illustrates a model by which military organizations may update their own regimes in the pursuit

---

[24] House Armed Services Committee Subcommittee on Readiness, Statement by LTG Kevin W. Mangum, 114th Cong., 2nd sess., 2016, 7.

[25] Donald A. Van Patten, *Transforming the Aircraft Inspection Process* (Maxwell Air Force Base, AL: Air University, 2007), 22.

[26] Ibid., 11-12.

of similar efficiencies. Examples of airline-inspired RCM process updates can be found within the US Air Force and Marine Corps.

Airline Maintenance and RCM

The Maintenance Steering Group (MSG) is a task force of airline manufacturers and aviation stakeholders that has led major reforms in aviation maintenance since the 1960s. As aircraft became more common and more expensive to operate, the dual imperative of safely increasing availability while safely reducing maintenance labor drove repeated attempts to reform maintenance in both civil and military aviation. The first major output of the MSG, published in 1968 as MSG-1, was a decision logic for developing maintenance regimes that was more structured and deliberate than previous efforts. [27] This effort reduced maintenance labor for the Boeing 747-100 aircraft to approximately 66,000 manhours within its first major inspection interval, compared to over four million manhours for another contemporary plane.[28]

The success of MSG-1 spurred manufacturers and industry organizations to continue improving maintenance regimes. MSG-2, published in the 1970s, propagated familiar concepts in Army maintenance such as time-based and condition-based component repair schedules to other civilian aircraft. It also recognized that some components required condition monitoring, or physical inspections designed to ascertain component health, while others could run to failure with little consequence. While these advancements were important, the MSG-2 system suffered from its bottom up approach to maintenance: it focused entirely on safety achieved through avoiding component failure without concern for economics, and thus resulted in higher labor time

[27] Steven Bentley, "Notes on the Evolution of MSG-3 (Maintenance Steering Group Logic-3)," Sofema Aviation Services Blog, August 27, 2012, accessed December 02, 2017, https://sassofia.com/blog/notes-on-the-evolution-of-msg-3-maintenance-steering-group-logic-3/.

[28] Dave Nakata, *Background Why Transition to a MSG-3 Based Maintenance Schedule?* (Frisco, TX: EmpowerMX, 2011), 1-3.

compared to its predecessor. Additionally, by approaching maintenance from the bottom up, MSG-2 derived regimes did not consider failures which might be hidden to pilots.[29]

The reliability-centered maintenance (RCM) construct arose out of a 1978 effort between United Airlines and the DoD to improve upon MSG-1 and MSG-2. Two key findings arose from this effort: first, that a preventative regime of scheduled overhauls only improves the reliability of a complex system if that system has a dominant failure mode, and second that there are many aircraft components for which no form of scheduled maintenance will effectively improve reliability.[30] RCM is a methodology for designing maintenance regimes, which ideally feature the best mix of maintenance philosophies and technologies for each system. RCM is additionally designed for iterative improvements, allowing a maintenance regime to evolve over the lifespan of a given system.[31] An RCM analysis is a fundamentally top-down approach which focuses on how component failures affect overall system reliability, rather than emphasizing component failures as the predominant concern.[32]

MSG-3, the third and current evolution of the Maintenance Steering Group's design, emerged in 1980 when the Air Transport Association incorporated RCM into an approach for airline maintenance. Because it is inherently iterative and responsive to change, MSG-3 remains the current process to develop and improve airline maintenance regimes. Between 1980 and 2011, ten major revisions to MSG-3 ensured it remained at the forefront of designing safe, economic maintenance regimes. New aircraft can incorporate MSG-3 analysis to ensure that their physical

[29] Steven Bentley, "Notes on the Evolution of MSG-3 (Maintenance Steering Group Logic-3)."

[30] F. Stanley Nowlan and Howard F. Heap, *Reliability-Centered Maintenance* (San Francisco, CA: United Airlines, 1978), 6-10.

[31] US Army Aviation and Missile Command, *United States Army Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy*, 5-6.

[32] Donald A. Van Patten, "Transforming the Aircraft Inspection Process," 94.

configuration does not produce redundant maintenance practices. This process is also applicable to redesigning maintenance routines of older aircraft, allowing operators of aging aircraft to ensure their maintenance practices yield the best economy, availability, and safety. Aircraft operators and manufactures use MSG-3 to design regimes for their aircraft, and FAA approves the resulting maintenance programs.[33]

Both MSG-3 and RCM are methodologies used to design maintenance regimes that maximize system availability and manage the consequences of potential failures. MSG-3 is essentially the commercial aviation version of RCM, and has benefited from nearly four decades of incremental improvements in an industry which is less risk tolerant and flies more hours per year than any of the military services.[34] While the DoD mandated the use of RCM when developing maintenance regimes for new systems in the 1980s, the Secretary of Defense eliminated this requirement in 1994. The current AR 750-1 again mandates an RCM approach for new acquisitions, but long aircraft lifespans mean the DoD operates a significant number of aircraft whose maintenance regimes have not kept pace with MSG-3's innovations.[35]

DoD Examples Outside of the Army

The high visibility and expense of military aircraft programs make them likely targets during budget reductions. The complicated nature of these programs means low readiness, cost overruns, and necessary modernization are routine qualities of aircraft acquisitions. More broadly, the DoD's Major Defense Acquisition Program, which includes aircraft acquisitions, experienced a $173 billion growth in cost overruns between 2008 and 2015.[36] The average schedule delay for

[33] Donald A. Van Patten, "Transforming the Aircraft Inspection Process," 94.

[34] "Airline Data Project," Massachusetts Institute of Technology, accessed December 07, 2017, http://web.mit.edu/airlinedata/www/Aircraft&Related.html.

[35] Donald A. Van Patten, "Transforming the Aircraft Inspection Process," 94.

[36] Robin S. Lineberger, *Still Late and Over Budget* (New York, NY: Deloitte, 2017), 2.

acquisitions also grew to nearly thirty months during this period. These qualities, while certainly undesirable, create persistent facts about operating military aircraft: the next generation will arrive later and cost more, while the current generation flies beyond its intended lifespan.

Because the Army must modernize and sustain the current generation of aircraft at increasing cost during their extended lifespans, the same budget competition threatens current aircraft availability. Emerging capabilities, new technologies, and accumulated flight data can enable cost reductions for operations and maintenance, while maintaining or improving safety and availability. An RCM regime for a given aircraft must then be updated over its lifespan to ensure it continually offers the best mix of maintenance practices given the capabilities, technologies, and data available at the time. Coincidentally, the benefits of MSG-3 RCM regime design are magnified when applied to older aircraft types, owing to available historical data and technical knowledge.[37] The United States Air Force (USAF) and United States Marine Corps (USMC) offer useful examples of military services updating maintenance regimes for existing aircraft.

The US Air Force's C-5 Galaxy aircraft is a large cargo platform used for strategic airlift and transportation. Facing similar pressures for reducing operating costs, the Air Force put half of its 112 C-5s into storage, curtailed its modernization program, and kept eight of the remaining fifty-six aircraft in non-flying status.[38] The C-5 is the only aircraft of its size available to the US military, and with the longest range of any US aircraft each one represents a significant capability for American power projection. Of the forty-eight aircraft still on flight status, only thirty-seven

---

[37] Unknown. *Maintenance Steering Group-3 (MSG-3)-based Maintenance and Performance-based Planning and Logistics (PBP&L) Programs* (Madison, AL: Intergraph, 2006), 3.

[38] John M. Donnelly, "To Save Millions, the Air Force Grounds Planes Worth Billions," *Task and Purpose*, April 15, 2017, accessed October 14, 2017, https://taskandpurpose.com/c5-galaxy-planes-grounded-air-force/.

received long-awaited modernization upgrades. Predictably, this reduction in strategic lift capability now justifies the expense of bringing two backup aircraft per year back into flying status, while resuming modernization of older airframes. The Air Force currently plans to fly the C-5 through 2040, meaning that fleet will have a service life exceeding seventy years.[39]

In 2009, the USAF transitioned part of its C-5 maintenance program into an MSG-3 derived regime to improve the fleet's low availability while reducing sustainment costs. This change included a review of the aircraft's maintenance regime, where a 'failure mode, effects, and criticality analysis' utilized historical data to reform or eliminate unnecessary maintenance procedures.[40] By focusing the maintenance regime on reliability, instead of identifying faults, each aircraft spends less time being inspected and is exposed to less potential human error. The projected long-term benefits of MSG-3 for the C-5 include an availability bump of seven additional aircraft every day, and a cost avoidance of $1.38 billion over the remaining aircraft lifespan.[41] In the first year, maintainers at Stewart Air National Guard Base using the MSG-3 procedures had improved C-5 fleet availability by 2.5 airframes per day, and increased mission

---

[39] Defense Industry Daily Staff, "Saving the Galaxy: The C-5 AMP/RERP Program," *Defense Industry Daily*, October 25, 2017, accessed November 29, 2017, https://www.defenseindustrydaily.com/saving-the-galaxy-the-c-5-amprerp-program-03938/.

[40] Failure Modes, Effects, and Criticality Analysis (FMECA) is a methodology for identifying the ways a system may fail, ranking potential failures in terms of their severity, and aiding the design of a process seeking to minimize overall failure risk. In RCM regimes, FMECA analyses of the aircraft system serve as the baseline picture of risk, to which various maintenance processes are applied in pursuit of maximum overall reliability.

[41] Holly Birchfield, "C-5 MSG-3 Brings Cargo Fleet Better Inspection Process to Keep Aircraft Flying," *Robins Air Force Base News*, August 17, 2007, accessed December 14, 2017, http://www.robins.af.mil/News/Article-Display/Article/379236/c-5-msg-3-brings-cargo-fleet-better-inspection-process-to-keep-aircraft-flying/.

capable rates by eight to fourteen percent.[42] Changes such as these will help the C-5 fleet weather budgetary turbulence while providing better dollar value and reliability.

Importantly, the USAF also considered wider reforms to the C-5 to improve holistic operating value. One such change involved the consolidation of major maintenance facilities from eight sites to four, saving the expense of nearly sixty jobs and over $80 million of required support equipment.[43] This change does not directly correlate with a potential reform in Army Aviation, where helicopter maintenance is primarily performed at each aircraft's assigned location. The largest helicopter repair facility in the world, Corpus Christi Army Depot (CCAD), does however perform in-depth scheduled maintenance on Army helicopters. CCAD's employee rolls dwindled from 6,226 to 4,024 between 2011 and 2016, exacerbating the need for aviation units to perform efficient scheduled maintenance in pursuit of the Army's readiness goals.[44] Another USAF change to the C-5 program leveraged High Velocity Maintenance (HVM), an approach to depot maintenance which reduces overall inspection time by increasing maintenance man hours per day. Air Force examinations of civil aviation maintenance found that airline operators leveraged between four and ten times greater maintenance man hours per day of

[42] Michael O'Halloran, "Best Practices in Air Force Found in 105th Air Wing Maintenance," *New York State Military and Naval Affairs News*, September 29, 2010, accessed January 4, 2018, https://dmna.ny.gov/pressroom/?id=1285762702.

[43] Dave Huxsoll, "Logistics Innovations Impact Warfighters," *US Air Force News*, November 20, 2007, accessed January 4, 2018, http://www.af.mil/News/Article-Display/Article/125088/logistics-innovations-impact-warfighters/.

[44] Allan H. Lanceta and Brigitte Rox, "Depot Operations in Support of Army Aviation," *Army Aviation Magazine.com*, accessed January 4, 2018, http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1162-depot-operations-in-support-of-army-aviation.

scheduled maintenance than did military efforts.[45] The HVM approach reduces historically long depot maintenance times, rapidly returning aircraft to the fleet and improving availability.

The Department of the Navy, inclusive of the United States Marine Corps, currently operates 166 attack helicopters and 760 airlift, cargo, and utility aircraft.[46] Seeking improvements to maintenance efficiency for its expensive CH-53 heavy lift helicopter fleet, the Navy evaluated sister-service and commercial maintenance programs which might reduce operating costs while retaining capability. From this need arose the Navy's Fleet Common Operating Environment (FCOE), a 2012 data analysis program which outputs predictive maintenance recommendations that reduce flight-hour costs and increase performance and availability. Based on Sikorsky's S-92 civilian helicopter fleet management program, FCOE analyzes unit maintenance data, aircraft-generated CBM data, and logistics and sustainment systems data through several DoD computer information systems to create these recommendations. By investing in the software required to accomplish this, the Navy found that it can adapt similar FCOE results across multiple aircraft platforms. Originally designed for the CH-53E model, they expanded this process to the CH-53K acquisition. According to the Selected Acquisition Report for CH-53K, the FCOE will "provide near real-time comparisons of actual environmental, reliability, cost, and sustainment infrastructure performance against the established baselines" designed to lower overall ownership cost of the new model.[47]

---

[45] Unknown, "High Velocity Maintenance," *US Air Force Fact Sheets*, April 25, 2008, accessed January 2, 2018, *http*://www.af.mil/About-Us/Fact-Sheets/Display/Article/104603/high-velocity-maintenance/.

[46] US Department of Defense, *Annual Aviation Inventory and Funding Plan Fiscal Years 2017-2046*, 9-11.

[47] Unknown, "H-53 Heavy Lift Helicopter Program Uses Data Trends to Increase Reliability, Reduce Cost," *NAVAIR News*, November 7, 2012, accessed December 7, 2017, http://www.navair.navy.mil/index.cfm?fuseaction=home.NAVAIRNewsStory&id=5170.

Department of Defense, *Selected Acquisition Report (SAR) CH-53K Heavy Lift Replacement Helicopter*, (Washington, DC: 2017), accessed January 04, 2018, http://www.dtic.mil/dtic/tr/fulltext/u2/1019132.pdf.

Budget shortfalls, increased sustainment costs, and aging fleets affect all military aviation programs, and maintenance studies seeking better aviation value encompass other USAF aircraft types as well. A 2012 paper by Donald Van Patten cited a 176 percent increase in Air Force average fleet age between 1967 and 2007, with corresponding dollar and manpower increases required to sustain aircraft as they grew older. While this number is partially offset by subsequently-fielded new aircraft such as F-22, F-35, and V-22, legislative mandates preventing the retirement of older aircraft types mean the sustainment cost with respect to fleet age has not decreased.[48] The article additionally noted that the 1994 removal of DoD's RCM requirement "orphaned legacy equipment" by preventing their maintenance regimes from seeing the kind of iterative, end-to-end analysis and improvement which characterizes a reliability-centered approach. Legacy aircraft have, instead, seen only systematic administrative changes to the manufacturer's regime, leaving their fleets burdened by costly, inefficient processes. The Army has not acquired a new manned combat helicopter platform in over thirty years, and similarly languishes from expensive preventative maintenance practices that struggle to meet availability goals.

Van Patten's research analyzed potential economy and availability improvements on two such legacy aircraft: the F-15 fighter and KC-135 air-to-air refuel tanker. Using the partial MSG-3 regime for the C-5 as a model, Van Patten created estimates for each aircraft that show cost avoidance greater than the regime development costs within the first year of use. In dollars per aircraft, he priced the F-15 at $20,750 and the KC-135 at $18,870 for MSG-3 conversion. While Army rotorcraft are much more mechanically complex than typical fixed-wing airplanes, which might indicate higher regime development costs, the Army operates over 2,000 UH-60 Blackhawk helicopters, compared to just 482 F-15s and 530 KC-135s in the USAF. Accordingly,

[48] Donald A. Van Patten, "Transforming the Aircraft Inspection Process," 102.

a per-aircraft regime development cost should similarly be a drop in the bucket compared to the cost of sustaining that aircraft for just one year.[49]

Army Aviation's Potential

The potential for the Army's manned helicopter fleets to benefit from maintenance regime updates is high because much of the technological groundwork has already been laid. Reforming a maintenance regime for a combat aircraft is an enormous undertaking, but the currently-fielded CBM technologies and the Army's capacity for collecting and analyzing CBM data may facilitate such reform. Processes and regulations limit the Army's capacity to benefit from RCM regimes, rather than in any physical system the Army would need to acquire.

Current Fleet CBM Capabilities

Most of the Army's manned helicopters use condition monitoring technologies which record and analyze system performance, facilitate data collection for units, and provide some degree of fault indication to aircrews during flight. The AH-64 helicopter fleet uses the Modernized Signal Processing Unit, whose sensor suite monitors fifty aircraft components against baseline performance values. This system additionally automates some maintenance activities, and performs data collection for unit fleets.[50] Newer AH-64E model Apaches are testing a more advanced, System Level Embedded Diagnostics program intended to integrate real-time diagnostics with the existing maintenance systems so that maintenance units will be able to plan a repair while the aircraft is still flying.[51] This impressive capability does not,

---

[49] Donald A. Van Patten, "Transforming the Aircraft Inspection Process," *102*.

[50] Deta Adams, Brian Murphy, and Michelle Kochoff Platt, "Condition Based Maintenance Fleet Implementation and Maintenance Decision Making Through Utilization of Prognostics Data by Operational Units," *American Helicopter Society International* (Huntsville, AL: 2009), 2-3.

[51] Joseph M. Herman, and Oswald Ingraham, "Introducing the Future of Army Aviation Maintenance," *Army Aviation Magazine.com,* accessed January 4, 2018, http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1164-introducing-the-future-of-army-aviation-maintenance.

however, modify the preventative maintenance regime, and its utility in a combat environment where unrestricted communications may not be available remains to be seen. A similar CBM capability, the Health and Usage Monitoring System, operates on the Army's UH-60 helicopters, with a lesser degree of maintenance practice integration than seen on the Apache. The Army's least numerous helicopter, the CH-47, does not have a fleet-wide CBM system implemented to the same degree as either of the other platforms, though the capability is available.

Significant cost savings are already attributed to the Army's investment in these condition monitoring technologies. Savings in the first two years of fleet-wide implementation included a $24 million cost avoidance due to not replacing fifty-one helicopter engines operated beyond limits, $30 million worth of increased flight hours returned to the UH-60 and AH-64 fleets, and an estimated $49 million saved due to three AH-64 accidents avoided by the technology. Maintenance efficiency also improved, owing to improvements in maintenance test flight feedback and the elimination of a handful of now-redundant inspections.[52] Though promising, the fundamentally unchanged maintenance regimes hamper the potential for these savings to continue at such high rates. Importantly, the near ubiquity of CBM data systems installed on Army aircraft means that a fundamental process change, such as an updated regime, can exploit this technology to even greater effect.

Current Regulatory and Process Limitations

The Aviation branch continuously struggles to occupy a position of best value for the Army without fundamentally changing its most expensive activity: operations and sustainment. Budget concerns have spurred six major studies within Army Aviation since the 1990s, each

[52] Charlotte Adams, "HUMS Technology" *Aviation Today*, accessed September 20, 2017, http://www.aviationtoday.com/2012/05/01/hums-technology/.

leading to a predictably myopic cut in materiel or manpower while harming long term value.[53] Because operations seldom relent in the face of budgetary pressure, a reduction in sustainment costs has a high potential benefit to the dollar value of aviation operations. Contemporary Army Aviation changes have, however, left aircraft maintenance practices fundamentally static with only piecemeal updates to reflect new technological capabilities.

The phase maintenance inspection defined in TM 1-1500-328-23 is currently and has been the dominant preventative maintenance regime for Army aircraft since the 1980s and earlier. The current release of this document, dated 30 June 2014, did not significantly change the definitions or practices associated with preventative maintenance from its immediate predecessor released in 1999. During the intervening fifteen years, the Army fielded CBM technologies to eighty-five percent of its rotary wing aircraft but exploited this capability only in particular maintenance instances. Despite seeing obvious cost savings potential for occasional decisions, such as determining whether a maintainer needed to disassemble and inspect a drivetrain after the aircraft exceeded a performance limit, the use of CBM technology did not significantly change the preventative maintenance regime.

The current draft CBM+ Strategy document for Army Aviation advocates for updated maintenance regimes but focuses on broad concepts without identifying how to overcome the obstacles posed by current policies. This strategy identifies the need for Army Aviation to embrace CBM+, using CBM technologies, through a continuously refined RCM approach. It identifies common maintenance strategy goals, including increased readiness and reduced costs. Steps toward those goals are then divided into three phases, with the tasks of each phase assigned to responsible organizations. The strategy is conceptually comprehensive, but does not address

[53] Richard A. Martin, "Challenging the Sacred Assumption: A Call for a Systemic Review of Army Aviation Maintenance," School of Advanced Military Studies (SAMS) Monographs, Combined Arms Research Library Digital Library, accessed September 5, 2017, http://cgsc.contentdm.oclc.org/cdm/singleitem/collection/p4013coll3/id/3698/rec/1.

the inherent tension between emerging CBM information and legacy scheduled maintenance approaches. The document notes the shortcomings of time-driven maintenance regimes without a plan for transitioning from a phase maintenance centric policy to one enabling the CBM+ approach it describes.

Maintenance and sustainment costs, excluding manpower or operations, represent nearly half of the expense of each aircraft annually and over one-third of lifecycle costs.[54] Technical Bulletin (TB) 1-1500-341-01, *Aircraft Components Requiring Maintenance Management and Historical Data Reports*, is an Army manual that prescribes those aircraft components whose maintenance and documentation must reflect the components' lifespan. Put another way, every aircraft has many components whose remaining usable life changes with their age, expressed in calendar time, flight time, or both. TB 1-1500-341-01 contains an exhaustive list of thousands of such components for Army aircraft and defines the processes for maintaining and managing these items. The procedures in this manual are mandatory for "all activities maintaining, stocking, storing, issuing, modifying, repairing, and/or overhauling aircraft, aircraft components or assemblies" within the Department of the Army. The objective of those mandatory procedures is to ensure that a flight critical component, for example a hydraulic pump, will not operate beyond its expected lifespans without being repaired or replaced.

The components listed within TB 1-1500-341-01 are important because their management requirements define a category of maintained components called 2410 items. Three types of such components are defined: retirement change items, which are removed from service at the end of their life; time change items, which are overhauled at the end of their life and returned to the supply system; and condition change items which have no pre-determined lifespan and are removed only when necessary. Each of these thousands of items has its own maintenance

[54] Department of Defense, *Selected Acquisition Report (SAR) AH-64E Apache Remanufacture* (Washington, DC: 2015), 37-38.

history recorded on a Department of the Army (DA) Form 2410. Larger, more complicated, or more expensive 2410 items have their histories reported to AMCOM to ensure that maintenance histories follow components as they move through the national supply system and are issued to units.

TB 1-1500-341-01 lists over 800 components requiring 2410 documentation on the AH-64 aircraft alone. Major sub-systems, such as electronics or turbine engines, have pages of their own sub-components requiring special maintenance management. A 2009 report by the American Helicopter Society on Condition Based Maintenance within the AH-64 fleet identified that seventy-seven percent of Apache 2410 tracked components did not meet their expected on-wing service life. In other words, nearly eight out of ten time change or retirement change components required removal before the end of their prescribed lifespan.[55]

The primary causes of failure the 2009 report identified are nicks, scratches, or corrosion which exceed the allowable tolerance for damage but do not necessarily prevent the component from functioning. In response to this discovery the Fatigue Life Management Program sought to move away from a "worst-case scenario" regime, which assumes that any damage over the threshold may lead to failure, to one based on assessing actual accumulated damage. The goal of this move was to increase component on-wing time and reduce excessive part replacement.

Clearly a mismatch exists between the expected lifespan of these aircraft components and the worst-case scenario engineering approach taken to define their removal criteria. The Army's approach to maintaining its aircraft resembles the bottom-up methodology abandoned with MSG-2 almost forty years ago. While the Army mandates RCM for developing new maintenance regimes, those of existing aircraft rely fundamentally upon the same phase maintenance regime

[55] Deta Adams, Brian Murphy, and Michelle Kochoff Platt, "Condition Based Maintenance Fleet Implementation and Maintenance Decision Making Through Utilization of Prognostics Data by Operational Units," 4-5.

developed with their initial fielding. Updated regulations and maintenance practices, using RCM analysis to examine the broad spectrum of sub-systems and potential outcomes of varying degrees of failure, could enable greater 2410 item lifespan utilization with no physical change to the aircraft.

Data Mining to Improve Indicators

Nicholas Goodman's dissertation for the University of South Carolina titled *Application of Data Mining Algorithms for the Improvement and Synthesis of Diagnostic Metrics for Rotating Machinery* details a common approach for facilitating CBM, which is practiced by the Army. In this approach, digital sensors monitor mechanical systems such as helicopter drivetrains, feeding software whose algorithms can turn raw data into diagnostic or prognostic indicators of mechanical component health. CBM systems that Army helicopters currently use to generate sets of operating data during flights and maintenance. Information systems transfer that data from the aircraft to a centralized data warehouse.[56]

Vibration measurement and analysis is the most common path to collecting and analyzing CBM data on machinery with rotating components. Scientists use mathematical analysis of vibration signals to relate raw vibration data to the actual condition of a component. Commonly, vibration values match with performance thresholds to produce a diagnostic indicator of component health. Similar processes can produce prognostic indicators, or predictions about when a component will fail.

Goodman's report identified in 2008 that the US Army's rotorcraft fleet meets the conditions required to generate a condition monitoring dataset that is appropriate for data-driven

[56] Nicholas Goodman, "Application of Data Mining Algorithms for the Improvement and Synthesis of Diagnostic Metrics for Rotating Machinery," diss., 2011. University of South Carolina, 33.

enhancement through data mining.[57] The Army's CBM Data Warehouse is a repository for accumulating condition monitoring and usage monitoring data from aviation units. An estimated CBM data generation rate of 843 gigabytes per day is possible given an aircraft fleet as large as the Army's, though Goodman notes that the actual data generation is likely less than half of that. Still, this amount of flight data creates a heavy burden on the CBM Data Warehouse to store it, and on military communications infrastructure to move the data between flying units and the warehouse. Thankfully, required sample sizes to identify population-wide normal usage data are smaller than the total amount of data generated and less than two percent of data generated is likely to influence a maintenance decision.[58]

Goodman demonstrates that the Army can use a data mining approach against such a warehouse to overcome some of the limitations associated with current condition monitoring schemes. He proves that the 2008-current data collection devices on board the AH-64 fleet generate sufficient data for the CBM Warehouse to use "the simplest of data mining algorithms" to derive fault indicators. Those indicators produce diagnostic information about aircraft condition.[59] From accurate diagnostic information about component life, it may be possible to make prognostic indicators that enable maintenance decisions based on actual remaining lifespan rather than worst-case engineering predictions.

Two important conclusions are evident about the capacity of currently-fielded Army Aviation technology: the potential to improve CBM practices increases as the Army continues to generate flying data, and that the expense of collecting and storing that data should be offset by its use to improve maintenance efficiency. This does not imply the Army has not already accomplished the data mining for which Goodman advocates to some degree, or that the analysis

---

[57] Ibid., 33.

[58] Ibid. ,47.

[59] Ibid., 82.

required for process improvements is not expensive or time consuming. However, as MSG-3 demonstrates, maintenance regime reform yields greater benefits for older aircraft types, whose available historical data informs the reliability-centered approach. The ages of the Army's manned helicopters mean such data is currently available.

The Current Plan

Army Condition Based Maintenance-Plus 2017-2027

In 2016 the Department of the Army G-4 office published an Army-wide strategy for implementation of CBM+, titled the *Condition Based Maintenance-Plus 2017-2027 Strategy*. This strategy aims to "create an enduring CBM+ capability in the Army" by defining requirements necessary for the Army to implement CBM+ across the enterprise. The document notes that fourteen years elapsed between the DoD mandate for CBM+ and the publishing of an Army strategy for implementation, but describes the Army as "now ready." The goals for the strategy are familiar to most DoD and civilian maintenance programs: increased sustainment efficiency and safety, resulting in improved availability and cost. It describes itself as both a living and directive document.[60]

The strategy describes a conceptual ten-year plan for integrating CBM+ into Army fleets and across all three levels of war. That plan contains three maturity stages: Stage I focuses on the capability to move maintenance data from a generating platform to an enterprise-level analysis effort. Stage II integrates the levels of war concept, seeking a "collect, interpret, and exploit" capability for data moving from tactical units to the strategic level. Stage III describes achieving an enterprise-wide, automated usage and equipment condition system which enables the

[60] Department of the Army, *Condition Based Maintenance-Plus 2017-2027 Strategy* (Washington, DC: 2016), 2.

improved readiness and sustainment capabilities sought by CBM+. The Strategy additionally notes the value of RCM methodology integration already mandated by Army Regulation 750-1.[61]

While the Army CBM+ 2017-2027 Strategy provides a conceptual roadmap for requirements development, its wide, high-level approach is fundamentally uncommitted. For example, Military Occupational Specialty (MOS) or technical qualification courses for Army Aviation maintainers do not teach them to use CBM technology to inform their maintenance decisions. Despite that education gap, Aviation units have employed CBM systems for over ten years, relying on experiential learning and on-the-job training to interpret condition monitoring data and make maintenance decisions. The strategy assigns Training and Doctrine Command (TRADOC) a deadline of 30 September 2020 to initiate development of a program of instruction for CBM+. If that program takes one to two years to develop, the first maintainers to receive an Army "schoolhouse" education covering CBM+ will not arrive at units until 2022, or more than fifteen years after those units began using the very technologies and processes behind CBM+.[62]

Army Aviation Branch Strategies 2017-2027

The Army Aviation Enterprise Sustainment Strategy (AAESS), one of several strategies developed by the Aviation branch, describes a modernization path for aviation sustainment over the 2017-2027 period. Published in 2016, the AAESS communicates Army Aviation's sustainment objectives and lines of effort to branch stakeholders and commercial partners. Five lines of effort and five goals or ends array across a familiar near, mid, and far-term phase plan. The plan considers each in terms of the DOTMLPF-P[63] framework, and the AAESS designates an

---

[61] Department of the Army, *Condition Based Maintenance-Plus 2017-2027 Strategy,* 7-8.

[62] Department of the Army, *Condition Based Maintenance-Plus 2017-2027 Strategy,* 15-16.

[63] Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities, and Policy is the framework within which the DoD considers solutions to capabilities gaps.

Office of Primary Responsibility which should later develop a detailed plan for achieving the goals.[64]

Table 1: Army Aviation Enterprise Sustainment Strategy Lines of Effort

Line of Effort	Office of Primary Responsibility	Goal
Acquisition and Modernization in Support of Sustainment	Program Executive Office – Aviation G-4	"Ensure Army aviation systems are designed, procured and modernized to: reduce total life-cycle costs, reduce maintenance man-hour (MMH)/flying hour (FH) costs while improving system readiness."
Sustainment Capacity and Capability	AMCOM G-5	"Maximize the Army aviation enterprise sustainment capabilities, resources and requirements to drive down overall sustainment burden and costs."
Processes, Practices, and Doctrine	US Army Aviation Center of Excellence (USAACE) Directorate of Training and Doctrine	"Relevant, clear and adaptive aviation sustainment doctrine that enables decisive action readiness in aviation operations."
Sustainment Leader and Soldier Development	USAACE G-3 Proponency	"Develop Army Aviation maintenance leaders and Soldiers with requisite knowledge, skills and experience gained through managed training and educational opportunities to improve readiness."
Policy, Regulation, and Reporting	HQDA Deputy Chief of Staff G-4	"Provide policy and guidance that enables the aviation enterprise stakeholders and partners to sustain aviation system airworthiness and improve readiness."

Source: K. Todd Royar and Thomas J. Barthel, "Army Aviation Enterprise Sustainment Strategy," *Army Aviation Magazine.com*, accessed November 30, 2017, http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1294-army-aviation-enterprise-sustainment-strategy.

The AAESS describes five unordered lines of effort leading to five goals or ends: Acquisition and modernization in support of sustainment, which seeks to reduce the logistics footprint and sustainment costs of new equipment. Sustainment capacity and capability, which also seeks to reduce the financial and logistic burden of sustaining aircraft. Processes, practices,

64 K. Todd Royar and Thomas J. Barthel, "Army Aviation Enterprise Sustainment Strategy," *Army Aviation Magazine.com*, accessed November 30, 2017, http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1294-army-aviation-enterprise-sustainment-strategy.

and doctrine is focused on sustainment doctrine which will facilitate higher readiness. Sustainment leader and soldier development, which seeks to link maintainer technical proficiency with promotion potential. Finally policy, regulation, and reporting, which identifies that current regulatory and reporting requirements may cause inefficiency and inaccuracy when describing aviation readiness.

The five resulting ends strike similar chords: reduced logistics footprint, reduced soldier burden, improved operational availability, expeditionary aviation force, and decreased costs, all hint at an aviation force which does more, costs less, and is easier to sustain.[65] Like the Army CBM+ 2017-2027 Strategy, the AAESS illustrates a conceptual commitment to modernizing sustainment, but does not modify current policies, regulations, or procedures which might enable immediate realization of some of its goals. While broad guidance in other military activities may foster subordinate initiative, there is simply no room for it aviation maintenance. The very purpose of the voluminous specificity found in aviation maintenance doctrine is removal of a maintainer's ability to interpret requirements, which might wager the aircraft against individual judgment. Also like the CBM+ Strategy, it addresses current sustainment issues primarily in name, and addresses potential solutions with vague generalities. One near-term solution proposed under the Sustainment Capacity and Capability line of effort is "enforce regulations and hold people accountable." A mid-term solution under the same category is "enforce cultural change." Even with parenthetical explanations, these actions are much too vague to assist a maintenance manager with improving readiness or saving money.[66]

---

[65] "Expeditionary" in the AAESS context describes improving parts, tools, and transport commonality across different aircraft types to reduce the logistic burden of deployment.

[66] K. Todd Royar and Thomas J. Barthel, "Army Aviation Enterprise Sustainment Strategy," *Army Aviation Magazine.com,* accessed November 30, 2017, http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1294-army-aviation-enterprise-sustainment-strategy

Another document illustrating the state of aviation maintenance thinking is the US Army's *Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy*. Built upon the Army CBM+ strategy of the same name, the aviation version is also a directive document which strives to enable "increased Operational Availability; increased Expeditionary capability; reduced Soldier burden; reduced Logistics Footprint; and reduced Total Life Cycle Cost." It also divides the ten-year strategy period into near, mid, and far-term stages, and analyzes high-level requirements through a DOTMLPF-P framework.

Table 2: Army Aviation Enterprise CBM+ 2017-2027 Strategy Objectives

Near Term Objectives	Mid Term Objectives	Long Term Objectives
Aviation CBM Office	Implement Army Aviation Enterprise CONOPS	Reduce Lifecycle Costs
Establish CBM+ Integrated Process Teams	Integrate CBM+ Requirements in AR 750-1	Reduce Soldier Burden
Develop Army Aviation CONOPS	Integrate Aviation CBM+ Requirements in AR 95-4	Reduce Logistics Footprint through improved diagnostics, prognostics, and analytics
Develop CBM+ Resourcing Strategy	Integrate Aviation CBM+ execution in DA PAM 750-1	Increase Operational Availability
Quantify the Training gap in the Institutional Training Base	Integrate Aviation CBM+ execution in DAM PAM 95-4	Increase Expeditionary Capability
Identify CBM+ Airworthiness requirements for integration into Army Logistics Information Systems (LIS)	Institute CBM+ continuation training at the Field and Sustainment levels	Institutionalize Aviation CBM+ requirements in POM builds
	Implement CBM+ training in Aviation Sustainment Professional Military Education (PME)	Fully integrated in Army LIS systems
	Implement CBM+ Resourcing Strategy	
	Include Aviation CBM+ Requirements in Program Objective Memorandum (POM) submissions	
	Integrate Airworthiness Requirements into Army LIS	

Source: US Army Aviation Center of Excellence, "Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy" *(Washington, DC: 2016).*

The Aviation Enterprise CBM+ strategy explains the relationship of Reliability Centered Maintenance (RCM) to CBM and CBM+ within Army Aviation. It quotes AR 750-1's requirement that RCM be used to develop initial maintenance regimes for new equipment, and notes that it should also "continuously update and optimize a regime" to find the optimal combination of maintenance methodologies. AR 750-1 requires, and the strategy here notes, that Program Managers must continuously update maintenance regimes as experience and data accumulate for the system. While the strategy includes integration of CBM+ into AR 750-1 as a goal, the current regulation already includes RCM requirements with little effect on the amount of unnecessary scheduled maintenance already performed or the aircraft availability that maintenance can yield. It is unclear, then, what positive effect on readiness such a goal can have without more specifics than the document provides. It also notes, in Appendix C, that there is "no current over-arching governance of this post-fielding optimizing of the maintenance program."[67] The *Aviation Enterprise CBM+ 2017-2027 Strategy* establishes criteria for evaluating enterprise-level achievement of CBM+ milestones, but otherwise addresses maintenance regime updates only conceptually. The advancements made in civil and sister service aviation demonstrate that the difference between identifying the need for reforms and reaping the economic and readiness benefits of those reforms is commitment to the procedural updates which enable them. Like the previous strategies, it does not commit to regime modification within currently fielded systems or empower maintenance managers to strive toward its stated goals.

Evaluating the Current Plan

Each of the strategies evaluated here represents official thinking on how the Army will leverage existing and emerging technology to improve weapon system readiness and availability while lowering sustainment costs. All three use the DOTMLPF-P framework to identify what will need to change, and which agency will be responsible for changing it. Despite the strengths of these approaches, none of them advocate for maintenance regime reforms on current aircraft using capabilities that are already fielded. None of them commit to regulatory or process changes which could, right now, push toward the very availability and efficiency gains each advocates for. These strategies are fundamentally conceptual, and seem to be waiting for the next generation of aircraft rather than striving for regime change within the current fleet. Army Aviation's history of accepting modernization budget cuts to pay for extending the lifespan of existing aircraft shows

[67] US Army Aviation Center of Excellence, *Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy* (Fort Rucker, AL: 2016), 28.

the folly of this approach; the currently fielded aircraft will fly longer than intended while becoming more expensive to maintain.

Continuing the maintenance regime status quo until fielding the next generation of Army aircraft may be unrealistically optimistic. Aircraft acquisitions routinely cost more and take longer than anticipated. The V-22 Osprey's price tripled during its more than twenty year development, it's cost per flight hour peaked above estimates at over $11,000, and it struggled to attain relatively low operational readiness near sixty-three percent for years following fielding.[68] Aircraft lifespans routinely last longer than estimated; the Army's plans for the CH-47 Chinook platform will extend its service life to 100 years.[69] Aircraft maintenance also takes longer and costs more as airframes get older: the continued efforts of airline operators to reform maintenance regimes has given them greater availability and a cost plateau after twenty years of aircraft age, while army helicopter maintenance downtime has steadily increased over the past decade.[70]

The last time the Army completed the full development and fielding of a helicopter system was in 1984, when the first production AH-64A Apache entered service after eleven years of Advanced Attack Helicopter development.[71] Subsequent helicopter acquisition programs have either been iterative upgrades of existing platforms, commercial purchases for non-combat aircraft, or cancelled before fielding as in the RAH-66 and ARH-70. The underlying point is that

---

[68] US Congress, *The V-22 Osprey: Costs, Capabilities, and Challenges*, 111th Cong., 1st sess, 2009, accessed December 4, 2017, https://www.gpo.gov/fdsys/pkg/CHRG-111hhrg54387/html/CHRG-111hhrg54387.htm.

[69] Stephen Trimble, "US Army Outlines CH_47F Upgrades for 100-year Lifespan," *FlightGlobal*, March 31, 2015, accessed January 6, 2018, https://www.flightglobal.com/news/articles/us-army-outlines-ch-47f-upgrades-for-100-year-lifespan-410729/.

[70] Matthew Dixon, *The Maintenance Costs of Aging Aircraft: Insights From Commercial Aviation*, Santa Monica, CA: RAND, 2006; House Armed Services Committee Subcommittee on Readiness, Statement by LTG Kevin W. Mangum, 114th Cong., 2nd sess., 2016, 3-6.

[71] Boeing Corporation, "Boeing Marks 25th Anniversary of Apache First Flight Sept. 30," *Boeing.com Website*, accessed October 17, 2017, http://boeing.mediaroom.com/2000-10-02-Boeing-Marks-25th-Anniversary-of-Apache-First-Flight-Sept.-30.

the Army and its supporting manufacturers have not had to design a combat helicopter maintenance regime from the ground up in over thirty years. The RCM mandate of AR 750-1 remains satisfied as long as some incremental updates occur on currently fielded aircraft. Despite constant churning about the cost of Aviation sustainment, the Army continues to lag behind civil or sister service maintenance philosophies. Army Aviation must modernize regimes for current airframes if it hopes to gain the CBM+ benefits touted by its strategies before it fields the next generation of aircraft.

The current way forward for Army CBM+ is conceptual in nature and does nothing to help current maintainers leverage CBM, condition monitoring, or RCM to achieve any of the strategy goals. The intended effect of the current strategies seems to be to transition Army Aviation to a more advanced sustainment methodology by the time the next generation of aircraft are in development. Former Assistant Secretary of the Air Force for Acquisition William LaPlante, speaking to a panel of the House Armed Services Committee, recently reported that weapons system acquisitions delays are worse than at any point in the nation's history.[72] Recent aircraft acquisitions offer support to LaPlante's point; the F-35 suffered production delays up to thirty months, reducing the number of aircraft purchased; the V-22 acquisition paused multiple times after high-profile accidents; the Government Accountability Office reported KC-46 fuel tanker delays of at least one year, with more possible.[73] Many such examples show that the Army's next aircraft will probably arrive later than expected, and that the imperatives for

[72] Travis J. Tritten, "Delays in US Weapons Buying 'Worse Than Ever,' Says Former Air Force Acquisitions Chief," *The Washington Examiner*, May 17, 2017, accessed January 20, 2018, http://www.washingtonexaminer.com/delays-in-us-weapons-buying-worse-than-ever-says-former-air-force-acquisitions-chief/article/2623348.

[73] Tony Capaccio, "Pentagon Weapons Tester Casts New Doubts on F-35 Progress," *Dallas Star-Telegram*, December 7, 2016, accessed January 31, 2018, http://www.star-telegram.com/news/business/article119408453.html; "Bell Boeing V-22 Osprey," *Helis.com*, accessed January 31, 2018, https://www.helis.com/Since80s/h_v22.php; US Government Accountability Office, *KC-46 Tanker Modernization Delivery of First Fully Capable Aircraft Has Been Delayed Over One Year and Additional Delays Are Possible*, March, 2017, accessed January 31, 2018, https://www.gao.gov/assets/690/683688.pdf.

increased availability and reduced cost within our current aircraft will not get any weaker as time goes on.

Recommendation

The Army clearly has safety, economy, and readiness imperatives to motivate improvements to its aviation maintenance programs. The current maintenance regimes are outmoded by those in other organizations, which exacerbates the potential for human error to impact safety, economy, and readiness. Airline operators and other DoD services have demonstrated through modernized processes, such as MSG-3, HVM, and FCOE, that process updates can yield real benefits in each of those imperative categories. The Army's helicopter fleet possesses the technology groundwork and data infrastructure to begin such updates, and its age improves the potential benefits of regime modernization. The Army's own strategies pursue these ends and committing to regime reform is the obvious way to achieve them.

Army Aviation should support its own stated priority, and that of the Army, by improving readiness through the near-term adoption of more efficient maintenance processes on currently flying aircraft. Many other fleet-managing organizations have successfully modernized maintenance practices on existing aircraft, with measurable yields in availability, safety, and efficiency. Next generation aircraft, such as those in the Army's Future Vertical Lift program, are unlikely to arrive on time, within their current budgets, or in the availabilities necessary to justify retaining outdated inspection regimes. The technologies and data necessary to support such modernization exist in the Army's aircraft today, and updated maintenance regimes can drive the regulatory, training, and information systems changes necessary to support future aircraft. While the Army has delayed aviation maintenance regime modernization, the cost of the Army's readiness continues to rise.

Conclusion

Readiness for Army Aviation depends on a level of aviator proficiency which it will not achieve at current funding levels. MG Gayler's remarks to Congress stated that low maintenance proficiency is currently preventing the Army's aircraft from meeting its readiness standard. Specifically citing increased operating costs resulting from insufficient troubleshooting skills and maintenance experience, he echoes LTG Mangum's remarks that this reduced technical skill resident in maintenance units has impacts on both aircraft availability and maintenance costs. He stated that many aviation units defer maintenance actions because of cost, which further reduces maintainer experience and aircraft available for training.

Army Aviation suffers from a group of interrelated problems that compound and magnify each other: Complex missions require high levels of proficiency but entail unit movements that decrease calendar days available to fly. The dollars required to attain high levels of proficiency exceed the flying hour budget, but lower proficiency increases the potential for expensive human error. Previous reliance on contract maintenance support purchased short-term readiness, but robbed maintainers of proficiency, which has reduced availability, which harms readiness while increasing the potential for human error to make Army Aviation more expensive. Low availability and expensive flying produce deferred maintenance, which harms maintainer proficiency, while also reducing the hours available to fly, which harms aircrew proficiency, which makes flying more expensive. The only solution which fits within this aviation system is one that provides an unlimited supply of money, aircraft and aircrew, or risk tolerance. Failing that, the branch will have to change the system so that these relationships no longer compound to such negative effect.

Clearly the Army is not the only organization which fights these issues, but it is just as clear that other organizations have already fought them with greater success. Achieving readiness as an aviation force currently means improving unit readiness within the existing budget. Unit proficiency requires aircraft availability, which is the product of both the proficiency of the maintenance organization and the efficiency of the maintenance regime. A more efficient maintenance regime, run by more proficient maintainers, has the dual effect of improving aircraft availability while reducing the operating and sustainment cost per flight hour. With reduced cost and increased availability, the Army could fly more hours within the same budget, improving unit proficiency, and achieving the readiness so important to its mission.

Bibliography

Adams, Charlotte. "HUMS Technology" *Aviation Today.* Accessed September 20, 2017. http://www.aviationtoday.com/2012/05/01/hums-technology/.

Adams, D., Murphy, B., and Kochoff Platt, M. "Condition Based Maintenance Fleet Implementation and Maintenance Decision Making Through Utilization of Prognostics Data by Operational Units." *American Helicopter Society International.* Huntsville, AL: 2009.

Bentley, Steven. "Notes on the Evolution of MSG-3 (Maintenance Steering Group Logic-3)." *Sofema Aviation Services Blog*, August 27, 2012. Accessed December 02, 2017. https://sassofia.com/blog/notes-on-the-evolution-of-msg-3-maintenance-steering-group-logic-3/.

Birchfield, Holly. "C-5 MSG-3 Brings Cargo Fleet Better Inspection Process to Keep Aircraft Flying" Robins Air Force Base News, August 17, 2007. Accessed December 14, 2017. http://www.robins.af.mil/News/Article-Display/Article/379236/c-5-msg-3-brings-cargo-fleet-better-inspection-process-to-keep-aircraft-flying/

Boeing Corporation. "Boeing Marks 25th Anniversary of Apache First Flight Sept. 30," *Boeing.com Website.* Accessed October 17, 2017. http://boeing.mediaroom.com/2000-10-02-Boeing-Marks-25th-Anniversary-of-Apache-First-Flight-Sept.-30.

Defense Industry Daily Staff. "Saving the Galaxy: The C-5 AMP/RERP Program" Defense Industry Daily, October 25, 2017. Accessed November 29, 2017. https://www.defenseindustrydaily.com/saving-the-galaxy-the-c-5-amprerp-program-03938/

Dixon, Matthew. *The Maintenance Costs of Aging Aircraft: Insights From Commercial Aviation*. Santa Monica, CA: RAND, 2006.

Donnelly, John M. "To Save Millions, the Air Force Grounds Planes Worth Billions" Task and Purpose, April 15, 2017. Accessed October 14, 2017. https://taskandpurpose.com/c5-galaxy-planes-grounded-air-force/

Goodman, Nicholas. "Application of Data Mining Algorithms for the Improvement and Synthesis of Diagnostic Metrics for Rotating Machinery." 2011. University of South Carolina, 33.

Herman, Joseph M., and Ingraham, Oswald. "Introducing the Future of Army Aviation Maintenance" *Army Aviation Magazine.com.* Accessed January 4, 2018. http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1164-introducing-the-future-of-army-aviation-maintenance

Huxsoll, Dave. "Logistics Innovations Impact Warfighters" US Air Force News, November 20, 2007. Accessed January 4, 2018. http://www.af.mil/News/Article-Display/Article/125088/logistics-innovations-impact-warfighters/

Lanceta, Allan H., and Rox, Brigitte. "Depot Operations in Support of Army Aviation" *Army Aviation Magazine.com.* Accessed January 4, 2018. http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1162-depot-operations-in-support-of-army-aviation.

Latorella, Kara A., and Prabhu, Prasad V. "A Review of Human Error in Aviation Maintenance and Inspection." *International Journal of Industrial Ergonomics.* 26. 2000.

Lineberger, Robin S. *Stille Late and Over Budget*. New York, NY: Deloitte, 2017.

Martin, Richard A. "Challenging the Sacred Assumption: A Call for a Systemic Review of Army Aviation Maintenance." School of Advanced Military Studies (SAMS) Monographs, Combined Arms Research Library Digital Library. Accessed September 5, 2017. http://cgsc.contentdm.oclc.org/cdm/singleitem/collection/p4013coll3/id/3698/rec/1.

Nakata, Dave. *Background Why Transition to a MSG-3 Based Maintenance Schedule?* Frisco, TX: EmpowerMX, 2011.

Nowlan, F. Stanley, and Heap, Howard F. *Reliability-Centered Maintenance.* San Francisco, CA: United Airlines, 1978.

O'Halloran Michael. "Best Practices in Air Force Found in 105^{th} Air Wing Maintenance" New York State Military and Naval Affairs News, September 29, 2010. Accessed January 4, 2018. https://dmna.ny.gov/pressroom/?id=1285762702.

Royar, K. Todd, and Barthel, Thomas J. "Army Aviation Enterprise Sustainment Strategy" *Army Aviation Magazine.com.* Accessed November 30, 2017. http://www.armyaviationmagazine.com/index.php/archive/not-so-current/1294-army-aviation-enterprise-sustainment-strategy.

Trimble, Stephen. "US Army Outlines CH_47F Upgrades for 100-year Lifespan." *FlightGlobal*, March 31, 2015. Accessed January 6, 2018. https://www.flightglobal.com/news/articles/us-army-outlines-ch-47f-upgrades-for-100-year-lifespan-410729/.

Tritten, Travis J. "Delays in US Weapons Buying 'Worse Than Ever,' Says Former Air Force Acquisitions Chief" *The Washington Examiner*. May 17, 2017, accessed January 20, 2018. http://www.washingtonexaminer.com/delays-in-us-weapons-buying-worse-than-ever-says-former-air-force-acquisitions-chief/article/2623348.

Unknown. "High Velocity Maintenance" *US Air Force Fact Sheets*, April 25, 2008. Accessed January 2, 2018. *http*://www.af.mil/About-Us/Fact-Sheets/Display/Article/104603/high-velocity-maintenance/.

Unknown. "H-53 Heavy Lift Helicopter Program Uses Data Trends to Increase Reliability, Reduce Cost" *NAVAIR News*, November 7, 2012. Accessed December 7, 2017. http://www.navair.navy.mil/index.cfm?fuseaction=home.NAVAIRNewsStory&id=5170.

Unknown. *Maintenance Steering Group-3 (MSG-3)-based Maintenance and Performance-based Planning and Logistics (PBP&L) Programs.* Madison, AL: Intergraph, 2006.

"Airline Data Project." Massachusetts Institute of Technology. Accessed December 07, 2017. http://web.mit.edu/airlinedata/www/Aircraft&Related.html.

US Army Aviation Center of Excellence. *Aviation Enterprise Condition Based Maintenance-Plus 2017-2027 Strategy*. Fort Rucker, AL: 2016.

US Army Combat Readiness Center. "Flightfax Online Report of Army Aircraft Mishaps." Accessed November 17, 2017. https://safety.army.mil/Portals/0/Documents/ON-DUTY/AVIATION/FLIGHTFAX/Standard/2012/May_2012_Flightfax.pdf.

US Congress. House. Committee on Oversight and Government Reform. *The V-22 Osprey: Costs, Capabilities, and Challenges*. 111th Cong., 1st sess. 2009. Accessed December 4, 2017. https://www.gpo.gov/fdsys/pkg/CHRG-111hhrg54387/html/CHRG-111hhrg54387.htm.

US Congress. House. Statement of MG William K. Gayler to Armed Services Committee's Subcommittee on Readiness. 115th Cong., 1st sess., 2017.

US Congress. House. Statement of LTG Kevin W. Mangum to Armed Services Committee's Subcommittee on Readiness. 114th Cong., 2nd sess., 2016.

US Department of the Army. *Army Regulation 700-138 Army Logistics Readiness and Sustainability*. Washington, DC: Government Printing Office, 2004.

US Department of the Army. *Army Regulation 750-1 Army Materiel Maintenance Policy*. Washington, DC: Government Printing Office, 2017.

US Department of the Army. *Army Tactics, Techniques, and Procedures (ATTP) 3-04.7 Army Aviation Maintenance*. Washington, DC: Government Printing Office, 2017.

US Department of the Army. *Condition Based Maintenance-Plus 2017-2027 Strategy*. Washington, DC: 2016.

US Department of the Army. *DA Pamphlet (PAM) 750-8 The Army Maintenance Management System (TAMMS) Users Manual*. Washington, DC: Government Printing Office, 2005.

US Department of the Army. *Technical Manual 1-1500-328-23 Aeronautical Equipment Maintenance Management Procedures*. Washington, DC: Government Printing Office, 2014.

US Department of Defense. *Annual Aviation Inventory and Funding Plan Fiscal Years 2017-2046*. March 2016.

US Department of Defense. Department of the Army. *39th Chief of Staff of the Army Initial Message to the Army*, by GEN Mark A. Milley. September 2015.

US Department of Defense. *Memorandum for Secretaries of the Military Departments: Condition Based Maintenance Plus*. Washington, DC: Department of Defense, 2002.

US Department of Defense. *Selected Acquisition Report (SAR) AH-64E Apache Remanufacture (AH-64E Remanufacture)*. 2015.

US Department of Defense. *Selected Acquisition Report (SAR) CH-53K Heavy Lift Replacement Helicopter*. 2017. Accessed January 04, 2018. http://www.dtic.mil/dtic/tr/fulltext/u2/1019132.pdf.

US Department of Transportation. Federal Aviation Administration. *A Human Error Analysis of Commercial Aviation Accidents Using the Human Factors Analysis and Classification System (HFACS)*, by Douglas A. Weigmann and Scott A. Shappell. 2001.

US Department of Transportation. Federal Aviation Administration. *Human Factors Guide for Aviation Maintenance*. 2014.

Van Patten, Donald A. *Transforming the Aircraft Inspection Process*. Maxwell Air Force Base, AL: Air University, 2007.

Van Patten, Donald A. "Transforming the Aircraft Inspection Process." *Air Force Journal of Logistics*, no. 34 (2011).