INSTITUTE FOR DEFENSE ANALYSES

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I N S T I T U T E   F O R   D E F E N S E   A N A L Y S E S

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Executive Summary

Part of a broad effort by the Army National Guard (ARNG) to increase understanding of the relationship between investments in full-time support (FTS) personnel and the ability to perform the ARNG mission, this Institute for Defense Analyses research investigates the relationship between FTS personnel and aviation readiness. Specifically, we estimate how changes in the number of Military Technician (MilTech) aviation mechanics at Army Aviation Support Facilities (AASFs) servicing ARNG helicopters impact the length of time that aircraft are unavailable for flight operations due to having at least one open fault, while holding other factors constant.

AASFs are the most common aviation maintenance facility in the ARNG, with 88 facilities operating in fiscal year 2019. MilTechs are ARNG members who work for the ARNG as civilian FTS personnel in addition to their roles as drilling ARNG members. MilTechs perform the majority of helicopter maintenance at AASFs. For this analysis, the duration of maintenance downtime events—or fault spells—is the outcome of interest, defined as the length of contiguous time a helicopter cannot be flown due a maintenance requirement. This analysis examines H-60 helicopters, including UH-60 Black Hawks and HH-60 Pave Hawks. Comparable analysis of other helicopters (e.g., CH-47 Chinook and AH-64 Apache) was not possible because the required maintenance data was not fully reported for those systems.

Additional AASF MilTech mechanics increase aircraft ready hours

Using a flexible semi-parametric econometric model—estimated with data from September 16, 2010 to September 15, 2019—we find that increasing the number of MilTech mechanics at an AASF reduces the duration of H-60 helicopter maintenance downtime events to a statistically significant degree across facility sizes studied. For the average AASF of a given size, each additional MilTech mechanic decreases fault spell duration by 0.7% to 1.1%, holding constant features such as the number and type of other aircraft assigned to the AASF, upcoming deployments, outstanding parts orders, and facility specific effects. The magnitude of the impact of an additional MilTech mechanic at a specific AASF depends on several factors, among them the facility's baseline MilTech mechanic headcount and the facility's overall volume of work. We find that the marginal impact of an additional MilTech mechanic reduces fault spell duration for AASFs of all staffing levels studied, with smaller marginal increases as baseline MilTech manpower levels rise (decreasing returns to scale in MilTech mechanic manpower). In other words, holding overall work volume and other factors constant, a MilTech mechanic added at a facility with a lower-than-average MilTech mechanic headcount increases aircraft availability more than one added at a higher-than-average headcount facility.

Applying these findings to the AASFs and workloads for fiscal year 2019, adding an additional MilTech mechanic to each facility with at least one H-60 helicopter year (74 MilTechs total) would result in an additional 18,509 mission capable (MC) hours (or 771 additional MC days) across the ARNG H-60 helicopter fleet on average. A rough estimate shows that of the gain in MC hours, 94% or 17,449 hours are FMC hours, which at average observed usage rates would produce 353 additional flight hours. However, the estimated impact on FMC and flight hours rely on strong assumptions and are subject to selection biases.[1]

Due to the incomplete reporting of non-H-60 helicopter maintenance events, and because MilTech mechanics working on H-60 helicopters are indistinguishable in our data from those working on other helicopter systems at the same AASF, our estimates of the impact of MilTech mechanic staffing on H-60 helicopter readiness should be interpreted as approximating the lower bounds of their actual productivity. However, controls for non-H-60 helicopters were included to mitigate this effect.

Return on Investment (ROI) Comparisons for Various Potential ARNG Aviation Readiness Investments

For a rough ROI comparison, a year's wages for 74 additional WG-12 MilTech mechanics is about $4.8 million. Therefore, were a MilTech mechanic added to each ARNG AASF with at least one H-60 helicopter year, the resulting additional MC hours would cost approximately $262 per MC hour on average in additional annual wages. The ARNG could alternatively obtain an additional MC hour by borrowing a UH-60M Black Hawk at the much more expensive price of $2,920 per hour from a different Department of Defense (DOD) component.[2]

Another option to increase MC hours for ARNG H-60 helicopters would be to purchase new helicopters. A typical H-60 helicopter had 5,723 MC hours in fiscal year 2019. Based on our analyses, hiring an additional MilTech mechanic in each of the 74 ARNG AASFs with at least one H-60 helicopter year is roughly equivalent to gaining 3.2 additional H-60 helicopters. The gross weapon system unit cost of 3.2 new UH-60M Black Hawks is approximately $74 million.[3] Further,

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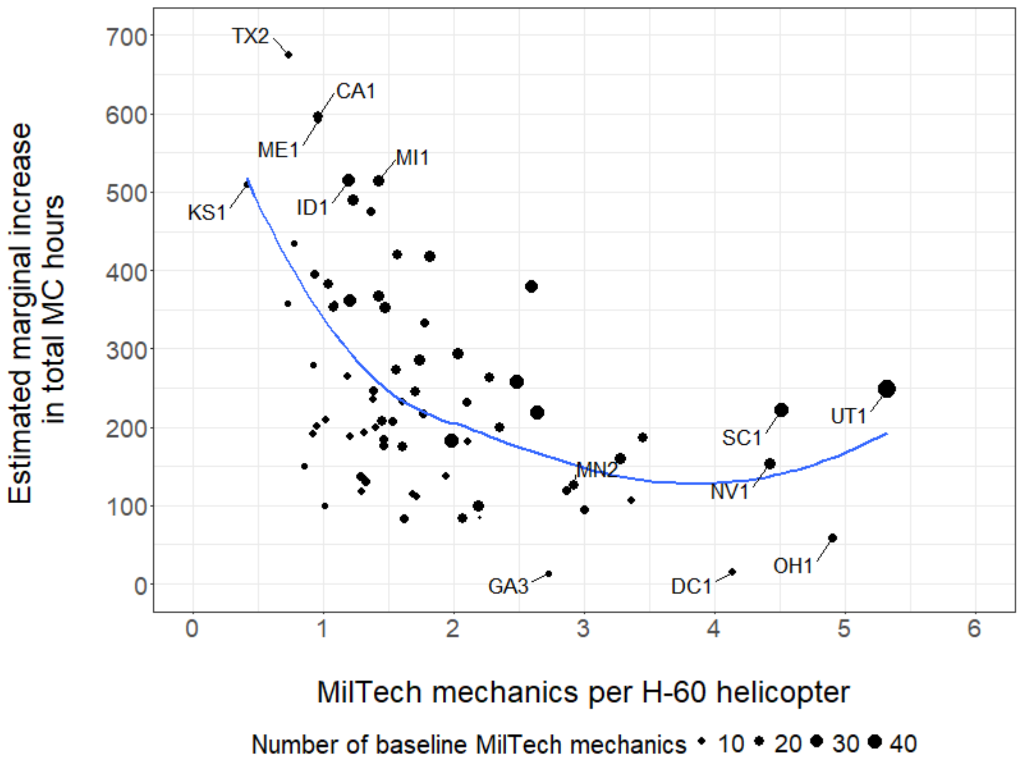
1 The flight hours are unexpectedly low because a helicopter that is rarely used tends to have low flight hours a large amount of MC time. Our simple models do not account for this bias.

2 Office of the Under Secretary of Defense, "Fiscal Year (FY) 2020 Department of Defense (DoD) Fixed Wing and Helicopter Reimbursement Rates," Oct. 2019, 1-8. www.comptrollerdefense.gov/ Financial-Management/Reports/rates2020/.

3 U.S. Department of Defense, Selected Acquisition Report (SAR): UH-60M Black Hawk Helicopter (UH-Black Hawk), RCS: DD-A&T(Q&A)823-341 (Washington, DC: Defense Acquisition Management Information Retrieval (DAMIR), December 2018), https://www.esd.whs.mil/Portals/54/Documents/FOID/ Reading%20Room/ Selected_Acquisition_Reports/FY_2017_SARS/18-F-1016_DOC_40_Army_UH-60M_Black_Hawk_SAR_Dec_2017.pdf.

the annual operating and support costs of 3.2 UH-60M Black Hawks would be $4.5 million per year.[4] We, therefore, conclude that additional MilTechs mechanics are a cost-effective means for expanding MC hours within the ARNG H-60 helicopter fleet.[5]



Note: Dot size is proportional to the number of total baseline MilTech mechanics, which include mechanics for H-60 helicopters, CH-47 Chinooks, and AH-64 Apaches. By contrast, the horizontal axis displays the ratio of total baseline MilTech mechanics per H-60 helicopter.

Marginal Effect of Additional MilTech Mechanics at ARNG AASFs on H-60 MC Hours

The figure illustrates the estimated additional H-60 helicopter MC hours for each AASF that would be realized if every AASF had an additional MilTech mechanic, based on the average MilTech mechanics per H-60 helicopter of AASFs in fiscal year 2019. The IDA team found that the marginal impact of an additional MilTech mechanic to be highest for AASFs with the least number of MilTech mechanics per H-60 helicopter at baseline. The positive returns of an additional MilTech decreases as the baseline number of MilTech mechanics per H-60 helicopter increases.

In this analysis, we investigate the impact of hiring additional MilTech mechanics on a measure of ARNG aviation equipment readiness. In fiscal years 2011 to 2019, we find that an additional MilTech reduces fault spell duration by between 0.7% and 1.1%, or an increase of

4 Department of Defense, "Fiscal Year (FY) 2021 Budget Estimates: Program Office Estimate for the UH-60M Black Hawk Helicopter" (Washington, DC: Department of the Army, February 2020).

5 This is a simplified comparison. MilTechs cost more than their salary due to benefits, training, etc.

23-to-30 MC hours per helicopter-year. If every AASF had an additional MilTech mechanic in fiscal year 2019, ARNG would have gained 3.2 MC helicopter years across its H-60 helicopter fleet. Compared to the cost of other methods considered, hiring additional MilTech mechanics is a cost-effective means of expanding MC hours within the ARNG H-60 helicopter fleet.

Contents

1. Introduction

A. Research Question and Analysis Scope

The Army National Guard (ARNG) relies on a fleet of approximately 1,430 helicopters (as of September 2019 readiness reporting) to help carry out its mission. To support its training and operational demands and meet its readiness targets, the ARNG must consistently maintain its helicopter fleet at a high level of readiness.

An aircraft's "readiness" or mission capable (MC) status indicates whether that aircraft is prepared to perform some or all of its designated missions in a given period of time, and is measured in available hours. When a helicopter requires certain repairs, or scheduled maintenance, it is considered "not mission capable" (NMC) for the designed mission set. Helicopter availability in an MC status can thus be increased by reducing the time required to resolve maintenance events. Maintenance time may be decreased in several ways, such as reducing time needed to obtain replacement parts, improving maintenance facilities, changing policies and standards, or increasing the number of mechanics.

This analysis estimates the impact of ARNG aircraft maintenance staffing levels—specifically, counts of Military Technician (MilTech) aviation mechanics at Army Aviation Support Facilities (AASFs)—on NMC time for aircraft serviced from September 16, 2018 to September 15, 2019. MilTechs are drilling ARNG service members who also work for the ARNG as civilian full-time support (FTS) personnel. The primary interest of this analysis is the duration of maintenance downtime events—or fault spells—an approximation for NMC time, defined as the length of time a helicopter cannot be flown due to a maintenance requirement.

To understand how or where additional resources can be most efficiently invested to produce additional available flight hours, one must first describe the relationship between the each of the inputs to the process, and what outputs result at various levels. This relationship is known as a production function. This analysis estimates a partial production function that relates the number of MilTech mechanics at a given AASF to fault spell duration for helicopters assigned to that AASF during fiscal year 2019.[6] Production functions of this type can be used to answer questions such as, "If I hire an additional MilTech mechanic at a given AASF and change nothing else, what

[6] The production function is partial because only one input, number of MilTech mechanics, has causal interpretation while all other inputs are held constant.

change in fault spell duration can I expect?" Figure 1 illustrates a notional production function for a single AASF.[7]

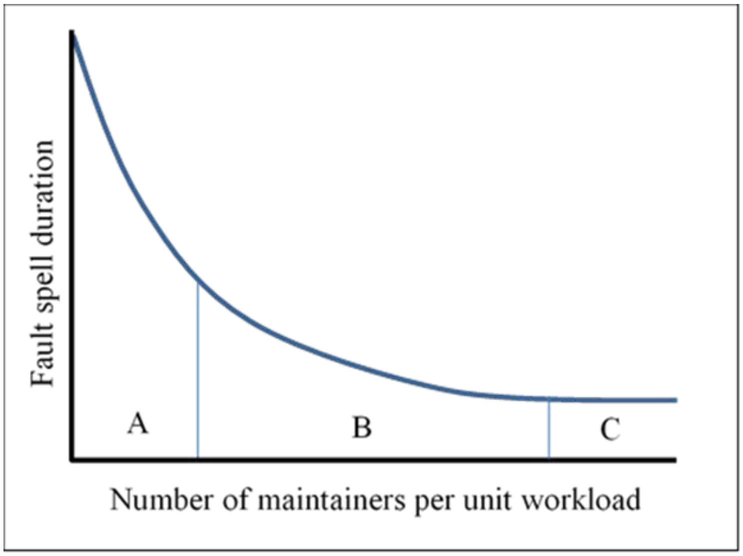


Figure 1. A Notional Maintenance Production Function

Figure 1 presents a notional production function with three regions labelled A, B and C. In region A, the AASF experiences increasing returns to scale: an X% increase in staffing reduces fault spell duration by an amount greater than X%. AASFs with staffing-to-workload levels in Region A are the most understaffed; consequently, readiness returns to additional manpower are highest in this zone. AASFs with staffing-to-workload levels in Region B experience a positive impact from additional manpower, but the magnitude of those positive returns decreases (a feature known as "decreasing returns to scale"): an X% increase in staffing reduces NMC spell duration, but by an amount less than X%. Additional mechanics allocated to AASFs in region B will help reduce fault spell duration, but not as dramatically for AASFs in region A. In region C, the AASF experiences no reduction in NMC time with additional manpower. AASFs in region C reach a staffing-to-workload saturation point where additional MilTechs do not help. The maintenance productivity of AASFs in region C is impacted by an input other than manpower (such as hanger bay availability or parts supply). This analysis identifies the true shape of the curve illustrated in Figure 1, and thus assists in allocating scarce resources to achieve greater readiness levels.

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7 It is important to note that each AASF has a different production function due to AASF-specific idiosyncrasies.

B. Literature

This analysis follows three prior IDA research projects on payoffs to FTS investments.[8] Pechacek [Lockwood], Wang, and Novak estimated an individual readiness production function, and identified a statistically significant and economically relevant positive relationship between investments in Title 32 Active Guard and Reserve (AGR) FTS and the deployability of individuals in units served by those AGRs. As anticipated, these positive marginal returns to additional AGRs diminished as the ratio of AGRs to drilling soldiers in a battalion-level unit increased. Pechacek, Kuo, Latshaw, and Novak also estimated a production function, and found that increasing MilTech mechanic manning levels in ARNG ground equipment repair facilities reduces the length of time required to complete vehicle work orders, thus improving equipment readiness.[9] Finally, Guggisberg, Pechacek, Wojtecki, Latshaw, and Graham considered the productivity of FTS serving in the offices of the United States Property and Fiscal Officers (USPFOs), and provided qualitative suggestions to improve operational efficiency.

In 2013, the Center for Naval Analyses[10] (CNA) produced a report for congress and the secretary of defense on the feasibility and advisability of eliminating the military technician (MilTech) as a distinct personnel management category within the Department of Defense (DOD). They recommended to "continue the [MilTech] program, although limited conversions to Title 5 civilian employees may be appropriate for positions that are inherently governmental but not military essential." A Title 5 federal civilian is employed as a civilian under Title 5 of the U.S. code. The 2016 National Defense Authorization Act (NDAA)[11] directed the DOD to convert at least 20 percent of its MilTechs to Title 5 federal civilians. The 2017 NDAA[12] deferred the deadline for conversion until a report was produced on the feasibility and advisability of converting any remaining MilTechs to Title 10 AGR, Title 32 AGR, or Title 5 federal civilian. That report,

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8 Julie Pechacek [Julie Lockwood], Allen Wang, and Ethan Novak, *Assessing the Effect of Title 32 Active Guard and Reserves on Personal Readiness in the Army National Guard*, IDA Paper P-8123 (Alexandria, VA: Institute for Defense Analyses, September 2016); Julie Pechacek, Dennis Kuo, Nathanial Latshaw and Ethan Novak, *Assessing Impact of Military Technicians on Ground Equipment Readiness in the Army National Guard*, IDA Paper P-10334 (Alexandria, VA: Institute for Defense Analyses, January 2019).

9 Julie Pechacek, Allen Wang, and Ethan Novak, *Assessing the Effect of Title 32 Active Guard and Reserves on Personal Readiness in the Army National Guard*, IDA Paper P-8123 (Alexandria, VA: Institute for Defense Analyses, September 2016).

10 Dolfini-Reed, et al., *Report on the Termination of Military Technician as a Distinct Personnel Management Category,* CNA Document DRM-2013-U-005399-1Rev (Arlington, VA: CNA Analysis & Solutions, September 2013).

11 National Defense Authorization Act for Fiscal Year 2016, Pub. L. 114-92, 129 Stat. 726, 114th Cong. (2015), https://www.congress.gov/114/plaws/publ92/PLAW-114publ92.pdf.

12 National Defense Authorization Act for Fiscal Year 2017, Pub. L. 114-328, 130 Stat. 2000, 114th Cong. (2016), https://www.congress.gov/114/plaws/publ328/PLAW-114publ328.pdf.

produced by McGee, Horowitz, and Kane,[13] analyzed the fully burdened costs of conversion, and the mix of AGR and Title 5 federal civilians to best support readiness. During the period studied, they found that MilTechs were less expensive than AGRs, and identified no particular readiness-related reason to prefer AGRs.

Within the equipment readiness literature, Bell and Teague compare the effect of phase maintenance versus progressive phase maintenance on MC time.[14] They find that phase maintenance is associated with more MC time. However, their study did not attempt to employ causal methodology and should not be interpreted causally.

Levine and Horowitz (2008) investigated ways for the Army to improve readiness of their helicopters using a descriptive statistical methodology to identify correlations between readiness and various equipment features.[15] They found that from 1980 to 2004, helicopter MC rates fell by an average of 1 percentage point per additional year of age, with a somewhat faster decline once age reached 14.5 years. They additionally found that from 2002 to 2006, the Army's 10-month recap program was associated with MC rates 13 percentage points higher than baseline for non-deployed helicopters, from 68 percent MC prior to start of the program to 81 percent MC afterwards. The MC rates of deployed helicopters rose somewhat less—by 6 percentage points, from 74 to 80 percent. Finally, Levine and Horowitz (2008) found that the average age of national backorders (formerly called wholesale backorders—those sent to CONUS depots) may be a reliable leading indicator of readiness. The analysis indicates that a 1-month increase in average backorder age would lower MC rates by 2.8 percentage points 5 months hence.

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[13] McGee, Horowitz, and Kane, *Analysis of Alternative Mixes of Full-Time Support in the Reserve Components,* IDA Document D-8575 (Alexandria, VA: Institute for Defense Analyses, August 2017).

[14] Z. M. Bell and L. T. C. E. Teague, "Comparison of Army Aviation maintenance methods via discrete event simulation," *2014 Systems and Information Engineering Design Symposium (SIEDS)*, Charlottesville, VA, 2014, 277–282.

[15] Daniel B. Levine and Stanley A. Horowitz, *Enhancing the Readiness of Army Helicopters*. IDA Paper P-4252 (Alexandria, VA: Institute for Defense Analyses, April 2008).

2. The ARNG Aviation Maintenance Environment

This chapter describes the ARNG aviation maintenance environment, including the helicopter fleet, maintenance facility types, factors that impact maintenance, types of maintenance, and types of maintenance personnel. This information was collected through site visits, literature reviews, discussions with subject matter experts, and reading published Army and ARNG documents. We also discuss potential measures of effectiveness for use in assessing the value-add of additional personnel.

Several documents comprise the ARNG technical guidance literature on aviation maintenance process and procedures. The most important of these reference materials for this analysis is Army Technique Publication (ATP) 3-04.7,[16] which provides guidance about aviation maintenance structure, organization, responsibilities, and functions focused from the aviation brigade to the platoon level.[17]

A. Helicopter Types

As of September 2019 readiness reporting, the ARNG maintained a fleet of 1,430 helicopters consisting of the UH-60 Black Hawk, HH-60 Pave Hawk, CH-47 Chinook, AH-64 Apache, and the UH-72 Lakota. Each platform has variants, with improved engines, rotor blades, electronics, and other components in each successive variant.[18] The ARNG retired the OH-58 Kiowa from their fleet in fiscal year 2016. The UH-60 Black Hawk is the most common ARNG helicopter, accounting for 66% of the ARNG helicopter fleet. The ARNG also maintains a small fleet of fixed-

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[16] Department of the Army, *Headquarters: Army Aviation Maintenance,* Army Technique Publication No. ATP 3-04.7 (Washington, DC, Headquarters Department of the Army, September 2017).

[17] Other documents used are Army Regulation (AR) 750-1, which covers Army policy for general maintenance operations and related topics; AR 95-1 (with NG supplement 1), which covers flight regulations; H-60-17-AMAM-11, which mandates a change in the phase schedule for UH-60 Black Hawks; AR 700-138, which establishes policies, responsibilities, and procedures to be followed for reporting the physical condition of Army equipment and the ability or inability to perform its intended mission; Department of Army Pamphlet (DA PAM) 738-751, which provides instructions for filling out forms related to aviation maintenance; National Guard Pamphlet (NP PAM) 750-2, which provides the responsibilities, policies, operations, and management of the ARNG Aviation Logistical Program for deployable Units, AASFs and Theater Aviation Sustainment Maintenance Group (TASM-G); Technical Manual (TM) 1-1500-328-23, which establishes maintenance and maintenance management standards of all Army aircraft and ancillary aeronautical equipment; and Continued Airworthiness Maintenance Plan (CAMP) for the Light Utility Helicopter, which outlines the day to day maintenance and operational procedures necessary for continued airworthiness of the UH-72A Lakota.

[18] The variant upgrade process is called recapitalization (or recap).

wing aircraft totaling less than 5% of total aircraft. ARNG fixed-wing aircraft is fully maintained by contract maintainers and the UH-72 Lakotas are partially maintained by contract maintainers, and are thus excluded from this analysis. Due to incomplete reporting of maintenance data (discussed later) the AH-64 Apache, CH-47 Chinook, and OH-58 Kiowa are also excluded from his analysis. Figure 2 presents a count of ARNG helicopters over time, excluding UH-72 Lakotas and fixed-wing aircraft.

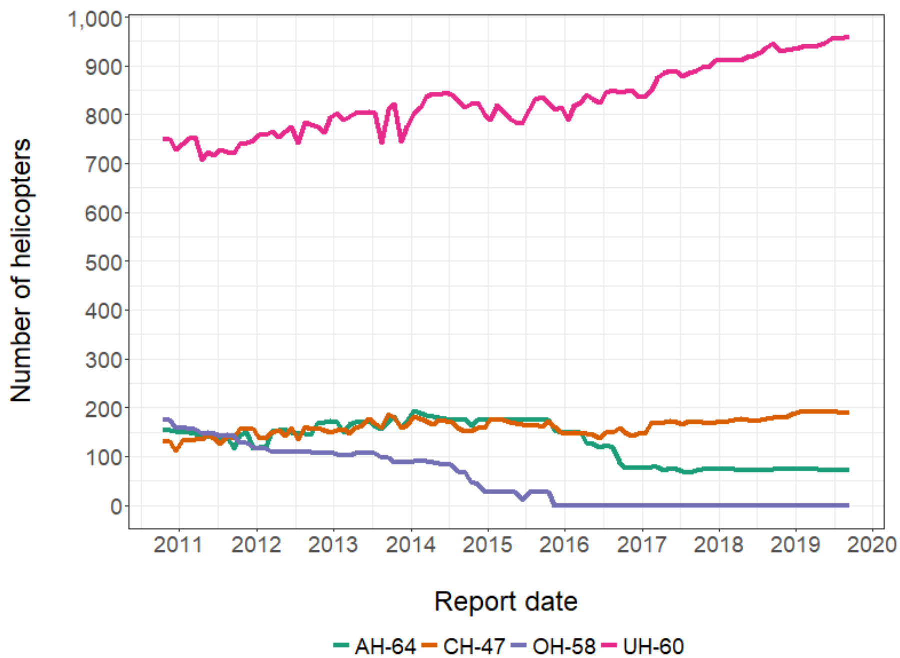


Figure 2. ARNG Fleet Size

The UH-60 Black Hawk is a twin-engine, medium-lift utility tactical transport helicopter that entered service in 1979. The primary missions of the UH-60 Black Hawk are troop transport and logistical support. The UH-60 Black Hawk also can be configured to support medical evacuation, command-and-control, search-and-rescue, armed escort, electronic warfare, and executive transport missions. Figure 3 depicts a UH-60 Black Hawk undergoing maintenance in an ARNG AASF. The ARNG also maintains a small fleet of 84 HH-60 Pave Hawk helicopters, which are derivatives of the UH-60 Black Hawk and include an upgraded communications and navigation suite. For this analysis, the term “H-60 helicopter” includes the UH-60 Black Hawk and the HH-60 Pave Hawk in three variants over the period of analysis: H-60A, H-60L, and H-60M. See Appendix G for information about the rest of the ARNG fleet.

Source: IDA.

Figure 3. UH-60 Black Hawk

B. Maintenance Facility Types

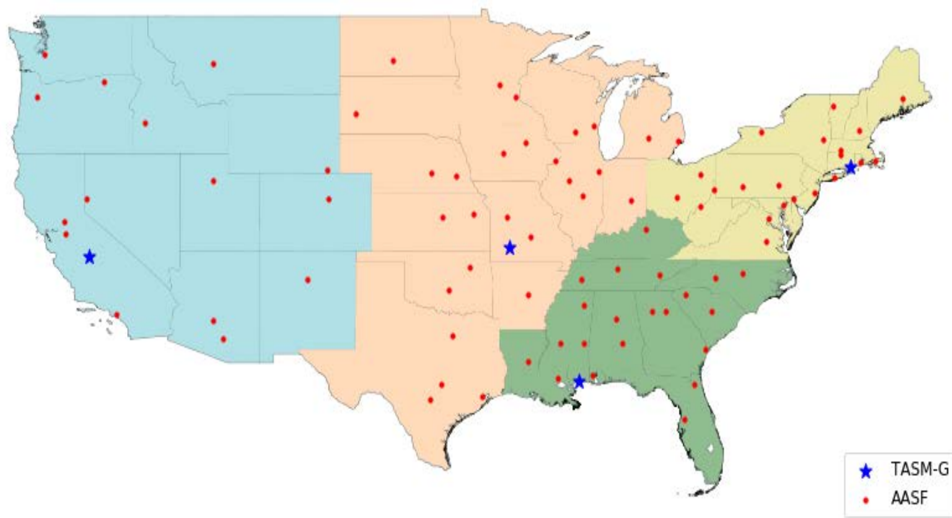
There are two main types of aviation maintenance facilities in the ARNG: the AASF and the Theater Aviation Sustainment Maintenance Group (TASM-G). AASFs provide field-level maintenance for the customer units that own the helicopters.[19] Various levels of maintenance are discussed in Section C.1. The customer units' helicopters are typically parked at the AASF regardless of whether the helicopter requires maintenance, or where the customer unit is located.[20] This analysis focuses on maintenance events at the AASFs. There were 88 AASFs in 54 U.S. states and territories in fiscal year 2019.

All U.S. states and territories are organized into four geographic regions, each supported by a TASM-G. Each TASM-G provides sustainment-level maintenance under license from the Corpus Christi Army Depot (CCAD), and can perform field maintenance as well. Maintenance types are described in section 2.C.1. Each TASM-G also has administrative duties, including setting regional maintenance policy, coordinating contract mechanics, coordinating allocation of helicopters amongst owning customer units, controlling regional ASL parts warehouse, and management of class IX air (i.e., parts) accounts. TASM-Gs provide specialized maintenance and thus support AASFs in states and territories outside their region. Figure 4 maps AASF (red dot)

[19] "Customer" refers to the operational owning unit whose helicopters are maintained by the given AASF.

[20] Customer units are typically located at AASFs.

locations and TASM-G (blue star) locations in the continental United States. The color blocks depicted in Figure 4 identify TASM-G regions.



Source: IDA

Figure 4. Facility Map

ARNG units are typically designated as deployable or non-deployable. TASM-Gs and AASF customer units are categorized as deployable units, while AASFs are non-deployable units.[21] For example, a MilTech employed full-time by an AASF can be a drilling member of—and deploy with—the AASF customer unit.

The majority of ARNG helicopters are parked at AASFs. AASFs account for 91% of reported helicopter months, with the remaining 9% of helicopter months at TASM-Gs or other sites. There are other types of aviation maintenance facilities but they are for atypical work. Limited AASFs (LAASFs), the Army Aviation Operations Facility (AAOF), and the Army Aviation Flight Activity (AAFA) perform a limited subset of the duties that a typical AASF performs and/or are temporarily staffed. ARNG Aviation Training Sites (AATSs) and the High Altitude Aviation Training Site (HAATS) provide aviation training and thus must be able to perform maintenance on-site. There are two AATS two locations: the Western AATS (WAATS) in Arizona and the Eastern AATS (EAATS) in Pennsylvania.

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[21] By deployable and non-deployable, we are referring to modified table of organization and equipment (MTOE) and table of distributional allowances (TDA) units respectively. The TASM-Gs transitioned from non-deployable units to deployable units by 2013. TASM-Gs currently perform six-month deployments on two-year deployment cycles, rotating through all four TASM-Gs. During site visits, the IDA team learned that the TASM-Gs do not typically perform sustainment-level maintenance while deployed and, consequently, their skills atrophy during deployed periods.

Organization Chart of a Typical AASF

Figure 5 depicts an example AASF organizational structure. An AASF commander is in charge of all operations and personnel at the AASF; contractors provide their own supervision. The AASF commander is subordinate to the state aviation officer (SAO). The AASF commander oversees three major sections: quality assurance, maintenance, and flight operations. The maintenance section organizes, prioritizes, and executes maintenance. The quality assurance section inspects maintenance after completion to ensure the maintenance was performed properly, and can alternatively be subordinate to the maintenance section. The final section—flight operations—is generally not related to the maintenance process. However, at some locations, the maintenance test pilots are subordinate to flight operations.

The logistics management officer (LMO) leads the maintenance section. The LMO is responsible for managing maintenance and logistics functions in support of customer unit training and operations. The LMO also provides logistical support to, and partners with, the AASF commander, flight operations, safety, quality assurance, and supports unit commanders in planning, scheduling, and implementing a comprehensive flying program. The maintenance test pilots perform diagnostics prior and during maintenance and perform final checks after maintenance is complete. The process control prioritizes maintenance and manages the maintenance staff. The maintenance staff consists of direct maintenance teams (i.e., "line maintenance") and backshops described in Section C.2.b. There can also be a dedicated phase team if the facility has enough MilTech mechanics to support such a team. See section 2.C.1 for a definition of phase maintenance.

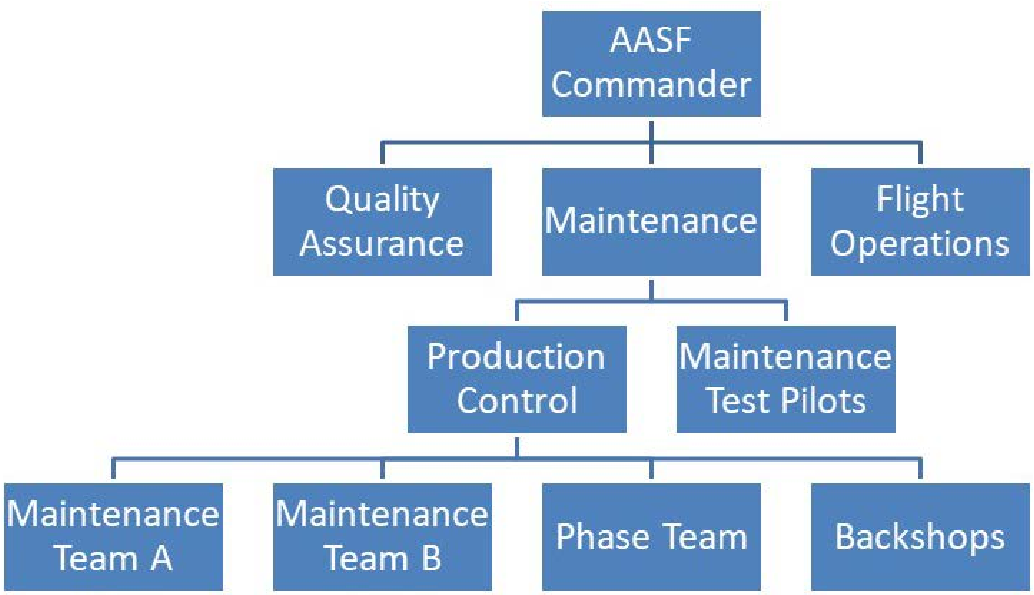

Figure 5. AASF Organization Chart

C. Factors That Impact Maintenance Duration and Frequency

Many factors impact maintenance duration and frequency, such as types of maintenance, skill and quantity of personnel, location, management, and military needs. Some of these will be correlated with total maintenance manpower. Identifying the causal effect of MilTech mechanics on fault spell duration requires including factors that are related to both MilTech mechanic headcounts and fault spell duration in the econometric model.

1. Types of Maintenance

The ARNG aviation maintenance strategy is designed to replace parts and equipment forward (in the operational setting) and repair in the rear (in the logistical setting). Thus, there are two levels in the hierarchy of maintenance: field and sustainment.[22] Field maintenance is on-system maintenance, generally replacing components or performing component repair and return to the customer. These include diagnosis, servicing, preventive maintenance intermediate, phase maintenance, special inspections, helicopter recovery and evacuation, helicopter weighing, maintaining authorized Operational Readiness Float (ORF) helicopters, minor airframe repair, avionics, and armament repair.[23] Sustainment maintenance is off-system and supports the supply system by economically repairing or overhauling components. The AASFs primarily perform field maintenance while the TASM-G facilities primarily perform sustainment maintenance. Variant upgrades (sometimes called recapitalization, or recap) are not performed at AASFs.

DA form 2408-13-1 is used as a record of maintenance; we refer to the information contained within it as “fault data.” Four main types of fault status are indicated by red X, circled red X, red dash, and red diagonal. Red X shows that a deficiency exists and the helicopter is not ready to fly. The other statuses are of varying levels of severity, but the helicopter can be flown. Approximately 19% of H-60 helicopter faults are red X.

Phase maintenance (simply called phase) is a regular scheduled maintenance program that accounts for 20% of the downtime for the average helicopter. During phase, the helicopter can be down for two-to-five weeks (depending on the type of phase) and will thus be unavailable for training, deployment, or state missions. Table 1 provides the current phase schedule for the AH-64D/E, CH-47F, and UH-60A/L/M (i.e., Apache, Chinook, and Black Hawk respectively).[24] The

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[22] Field used to be called Aviation Unit Maintenance (AVUM) and Aviation Intermediate Maintenance (AVIM). Sustainment used to be officially called depot; both terms are currently used interchangeably.

[23] ORF is a strategic asset deployed to an installation consisting of an authorized quantity of assets used to maintain established readiness levels or to meet training availability requirements during peace time. ORF assets are maintained by deployable and non-deployable maintenance activities with a field maintenance mission to exchange with supported units when repairs cannot be accomplished within the established guidelines.

[24] The UH-60 and HH-60 series of helicopters experienced a change in the phase schedule from 360/720 hours to 480/960 hours on August 2017 (Aviation Safety Network 2017). The AH-64 has a “125 hour phase” that appears in the fault data. Discussions with the ARNG aviation division concluded that the “125 hour phase” is not an official phase maintenance but a non-recurring inspection driven by the maintenance manual.

table shows the number of flight hours from the beginning of the phase cycle until a phase maintenance event must occur, and how long the phase maintenance event should take. The phase maintenance schedule is strict for the UH-60 Black Hawk and less strict for the other helicopters. After completion of the second phase maintenance event, the cycle repeats. For example, suppose a UH-60M Blackhawk completes the second phase maintenance event at 960 flight hours. Then at 1,440 flight hours, it must undergo the first phase maintenance event; at 1,920 flight hours, it must undergo the second phase maintenance event; at 2,400 flight hours, it must undergo the first phase maintenance event, etc. The helicopter pilot reports flight hours, which are different than engine hours. The OH-58 Kiowa had Progressive Phase Maintenance (PPM). PPM consolidates and replaces daily, phase, and special inspections. Its purpose is to minimize inspection requirements for increased mission flexibility and helicopter availability.

Table 1. Phase Schedule

Mission Design Series	Goals in Working Days
AH-64D/E	
1: 250 hours	11 days
2: 500 hours	26 days
CH-47F	
1: 200 hours	18 days
2: 400 hours	36 days
UH-60A/L/M	
1: 480 hours	20 days
2: 960 hours	30 days

Source: Department of the Army, *Headquarters: Army Aviation Maintenance,* Army Technique Publication No. ATP 3-04.7 (Washington, DC, Headquarters Department of the Army, September 2017).

2. Types of Maintenance Personnel

Maintenance personnel can be categorized by the authority they were hired under, by their specialty and skill, and by their tenure (experience) and turnover. The hiring authority determines the rules and regulations the individual and the AASF must abide by and how the individual is compensated. Their specialty and skill describes the type of work the individual is able to perform.

a. Hiring authority

Dual status MilTechs are the primary type of staff at AASFs. Figure 6 shows a MilTech mechanic performing maintenance. A MilTech is a full-time civilian employee of the ARNG who must maintain drilling membership with the ARNG. If they lose drilling status with the ARNG (e.g., leave voluntarily or involuntarily) they will lose their MilTech position. MilTechs work 40 hours per week, but they can work a varied schedule (e.g., Monday through Friday, 0800 – 1600; or Tuesday through Friday, 0800 – 1800). MilTechs can work more than 40 hours per week, but must be given compensatory time off; they are not eligible for overtime pay by policy. However, unofficial overtime can be paid through additional drills from the Additional Flight Training Period (AFTP) account, in which case, the MilTech works additional time as a drilling reservist and is paid as a reservist for the extra time worked.

Source: IDA.

Figure 6. MilTech Mechanic

The link between a MilTech position at AASFs and ARNG member is said to be compatible under CNGBI 1400.25, Vol. 303[25] if the ARNG member performs their military drill weekend duties with a customer unit at the AASF where they perform their weekday job. However, anecdotally compatibility is not required for employment. Thus, some MilTechs satisfy their drill duties at non-customer units. If a MilTech is deployed or mobilized, the AASF must keep that MilTech on its administrative staffing logs, and cannot hire full-time staff to replace the deployed MilTech. The AASF can hire a temporary technician (i.e., TempTech) for every three deployed MilTechs.[26] TempTechs can also be hired to assist with maintenance for an upcoming deployment.

[25] Department of Defense, "Dual Status Military Technician Compatibility Program," CNGBI 1400.25, Vol. 303 (Washington, DC: DOD (NGB-J1)).

[26] Sometimes, the vacated spots from deployed MilTechs are not filled. There are four (excepted service) tenure groups for technicians: 0) temporary employees; 1) permanent employees; 2) employees who are serving trial periods, or whose tenure is equivalent to career-conditional tenure in the competitive service in agencies that have that type of appointment (for example, excepted appointment-conditional); and 3) employees whose tenure is indefinite; that is, without specific time limitation but not actually or potentially permanent, or with a specific time limitation of more than one year; also, employees who, though currently under appointments limited to one

The 2017 NDAA made MilTechs eligible for Merit Systems Protections Board (MSPB) rights that federal civilian employees have to protect against abuses by management.

The AASF also has access to flexible staffing through Active Duty Operational Support (ADOS), TASM-G traveling teams, and contractors. The AASF customer units may hire personnel on ADOS (which are temporary orders). However, personnel brought in on ADOS orders typically assist with administrative duties for deployment and do not perform maintenance. The regional TASM-G may supply the AASF with temporary military or contractor manpower. The temporary military manpower travels from the TASM-G to the AASF. The additional manpower does not cost the AASF. The UH-72 is maintained by a mix of contractors and MilTechs in a program called "hybrid maintenance." The fixed-wing aircraft are maintained by contractors.

The customer unit is on site during drill weekends. However, drill weekends typically consist of training with the helicopters, not performing maintenance. However, some maintenance can occur on drill weekends by drilling ARNG reservists.

The AASFs and TASM-Gs do not employ Title 5 federal civilians.[27] During site visits, the IDA team asked about the effect of bringing Title 5 federal civilians into the maintenance process. The IDA team was consistently told that Title 5 federal civilians at AASFs would have a negative impact on overseas operations because the Title 5 federal civilian would deprive MilTechs of good experience. However, this effect did not seem to be as pronounced for TASM-Gs because there is a larger pool of FTS mechanics and much of the work overseas is already performed by civilians. This is discussed further in Appendix C.

b. Specialty and skills

Each ARNG member has a Military Occupational Specialty (MOS) code that describes his or her primary skill set. For example, avionic mechanics are designated by MOS code 15N and UH-60 Black Hawk repairers are designated by MOS code 15T. Likewise, ARNG members who are hired as MilTechs have an occupation series that identifies their occupation. Individuals are classified as a maintainer if they "touch" the helicopter or its mounted subsystems. Further, maintainers are classified as (direct) mechanics or backshop maintainers (indirect maintainers). Direct mechanics are primarily responsible to maintain their model of helicopter and have an occupation series of 8852. Backshop maintainers specialize in areas such as avionics, structural repair, powertrain, and powerplant, which cover electronics, sheet metal, prop and rotor, and engine repair. Maintenance test pilots and quality assurance personnel are also included in our

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year or less, complete one year of current continuous employment. Groups 0 and 3 are combined as temporary, referred to as "TempTech" and groups 1 and 2 as not temporary, referred to as "MilTech." This taxonomy applies only for this paper and may not be the same as other definitions of "MilTech" and "TempTech." Over the period of analysis, 4.4% of technicians are in group 0, 84.0% of technicians are in group 1, 6.6% of technicians are in group 2, and 5.1% of technicians are in group 3. This distribution does not change significantly over time.

27 There were some positions in the SAO office that converted to Title 5 federal civilian during the mass conversion.

definition of backshop because they are required to perform final inspections prior to a maintenance event ending.

A MilTech is commonly hired into a position that is functionally equivalent to the MOS the ARNG member holds. However, this does not always happen and is described as "non-compatibility." When non-compatibility occurs, the ARNG member can perform their MilTech job for up to one year without attending a required resident training program. At the end of the one-year period, the ARNG member's requirement to attend a resident training program can be waived for another year. This can occur every year indefinitely.

Figure 7 depicts the number of MilTech maintainers at any flight facility by type over time. As of September 2019, there were approximately 1,750 direct mechanics and 1,250 backshop maintainers. In fiscal year 2019, the 50th percentile (median) AASF had 1.5 MilTech mechanics per helicopter, the 10th percentile AASF had 0.8 MilTech mechanics per helicopter, and the 90th percentile AASF had 2.4 MilTech mechanics per helicopter.[28]

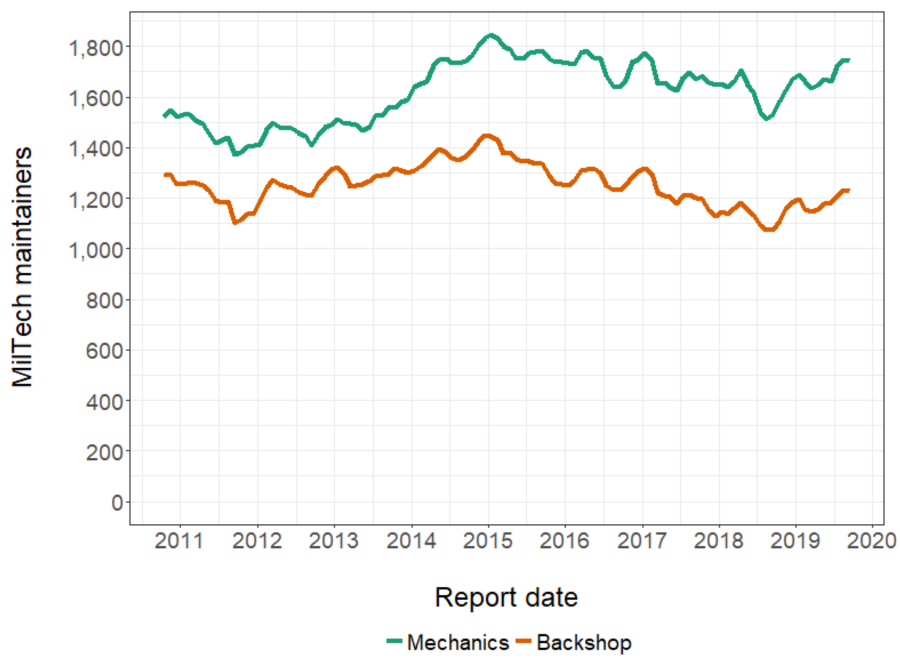

Figure 7. ARNG Aviation Maintainer Pool

c. Tenure and turnover

During site visits, AASF staff members informed the IDA team that MilTechs recruited in 2019 have noticeably less experience as helicopter maintainers than those recruited in 2012 and earlier, on average. AASF staff cited poor recruiting of prior service members, competition from the civilian sector, and poor retention in the ARNG as contributing factors to this experience

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[28] H-60 helicopters, CH-47 Chinooks, and AH-64 Apaches are included. UH-72 Lakotas are excluded.

decline. The IDA team investigated the statement (see Figure 8) and found a slight decrease in the military tenure of newly hired MilTechs from fiscal years 2011 to 2019.

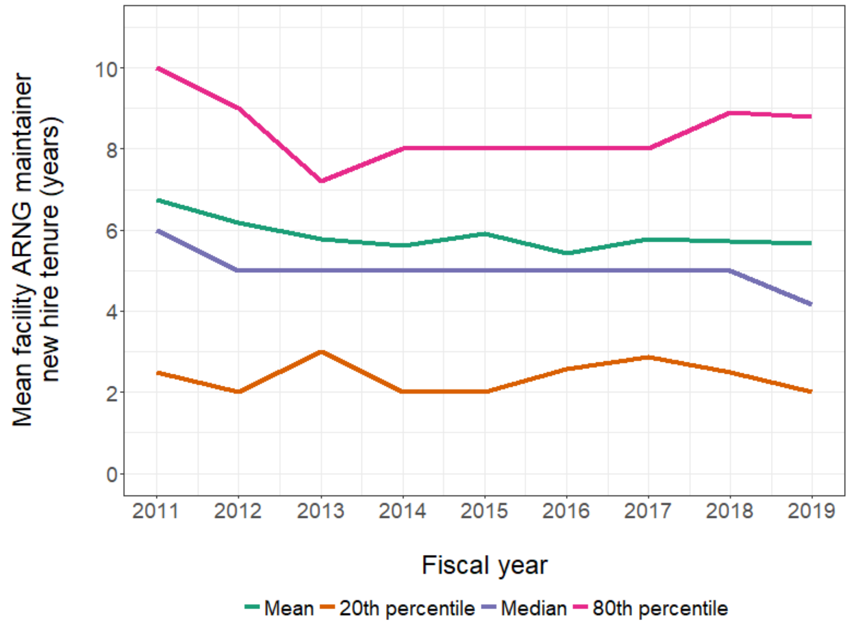

Figure 8. New Hire MilTech Maintainer Tenure

Turnover also relates to experience, and can impose inefficiency costs through increased training burdens and lack of familiarity with policies, procedures, and other personnel at the AASF. Every facility visited expressed frustration with high turnover. Figure 9 shows the mean, 20th percentile, median, and 80th percentile of MilTech turnover rate over time, calculated as the number of individuals who have departed within the calendar year divided by the average staffing level within the calendar year.[29] No turnover trend is evident over the period analyzed. In fiscal year 2020, the 80th percentile turnover rate was 0.17, meaning that 80% of AASFs experienced 17% or less of their average MilTech maintainers staffing level turning over.

[29] The average is over months. Turnover rate does not include TempTechs, or those who are mobilized or deployed. Turnover rate is bounded between 0 and 12, where 0 represents no turnover all year and 12 represents full staff turnover every month.

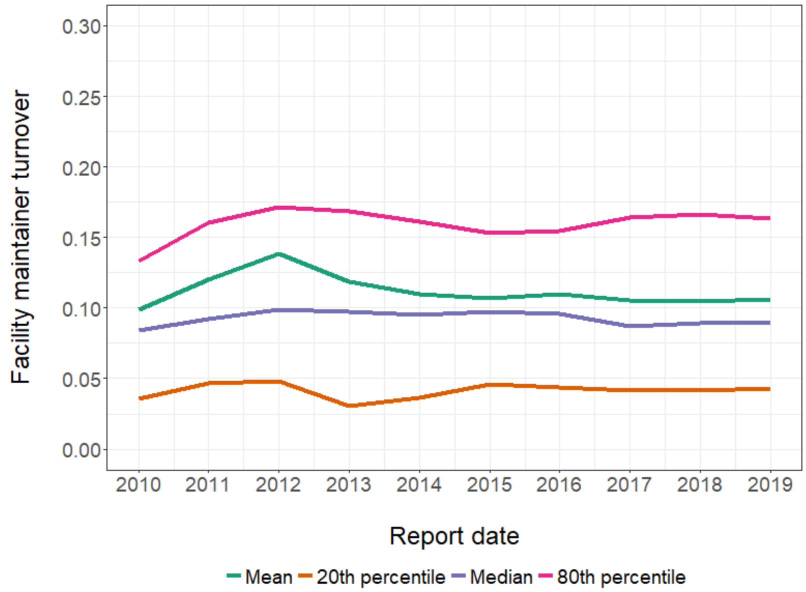

Figure 9. MilTech Maintainer Turnover

3. Other Factors

Other factors that impact maintenance frequency and duration include facilities, location, parts availability, helicopter characteristics, and ARNG training and missions.

Facility-specific factors that influence maintenance include limited hanger space AASFs that have limited hangar space are forced to park their helicopters outside, which can expedite deterioration of the electronic and other systems. The IDA team observed that, due to limited hangar space, the AASF in Connecticut sometimes must rotate the blades of a CH-47 Chinook so that the helicopter can be towed into the facility. Facilities that have fixed-wing aircraft usually store the aircraft inside the hangar, preventing helicopters from using that space. Extreme weather over uncovered hangar space adversely affects the durability of equipment. Figure 10 shows four UH-60 Black Hawk helicopters parked uncovered outside at an Arizona AASF hangar due to lack of space inside the hangar. July at that location has an average high temperature of 106 degrees Fahrenheit. Lastly, availability and serviceability of ground support equipment (e.g., lifting crane) also impact maintenance.

Source: IDA.

Figure 10. UH-60 Black Hawks Parked Outside

Availability of parts is crucial for timely maintenance. AASFs maintain two supplies of parts: bench stock and authorized stock list (ASL). Bench stock parts are low-cost, high-volume items used by maintenance personnel at a predictable rate. Examples of these items are common hardware, resistors, transistors, wire, tubing, hose, thread, welding rods, sandpaper, sheet metal, rivets, seals, oils, grease, and repair kits. ASL items are more expensive (see Figure 11). Bench stock is managed by the AASF, while ASL is managed at a higher level.[30] If a part is needed and unavailable, it can be ordered. While the part is being delivered, the AASF might borrow the part from a nearby AASF. When the part is delivered, the AASF will replace the borrowed part. AASFs can also perform a controlled exchange where working parts are taken off of another helicopter.

[30] AASFs used to have a Prescribed Loading List (PLL) prior to ASL, which AASFs managed themselves.

Source: IDA.

Figure 11. A Collection of ASL Parts

Helicopter-specific features are also important determinants of maintenance. Most obviously, the helicopter type matters because of differences in the systems onboard the helicopter. The age of the helicopter (measured in days since manufacture, engine hours, or flight hours) is important since older helicopters tend to have more maintenance problems. Helicopters with near-term surges in flying hours can have more issues that need to be repaired. Conversely, disuse also leads to maintenance issues of different types. Events in a helicopter's past, such as prior inadequate maintenance, hard landings, or other strenuous maneuvers can affect current maintenance requirements.

Lastly, the training and mission demands of the ARNG dictate much of the maintenance needs. Helicopters that are heavily used in training, state missions, or deployments will have more frequent maintenance needs. In addition, training timing impacts maintenance because the customer units desire to use helicopters during their training events, and thus need lower NMC rates just prior to and during training.[31] Maintenance needs, therefore, fluctuate around annual training (AT) events wherein helicopters are heavily used.

D. Measures of Effectiveness

The purpose of this analysis is to identify the impact of investing in MilTech mechanics. This requires defining an appropriate outcome measure. The outcome measure should satisfy six conditions and be: 1) relevant to helicopter readiness, 2) quantitatively measurable, 3) reasonably causally related to the number of MilTech mechanics, 4) common and comparable in meaning

[31] This is because NMC issues are resolved prior to training, not because they are delayed until after training.

throughout the ARNG and across time, 5) of high importance to the ARNG, and 6) accurately recorded and retained at sufficiently high frequency.

ATP 3-04.7[32] states that there are four measures of effectiveness for assessing the field maintenance operational ability to generate combat power. The measures of effectiveness are combat power, maintenance, technical supply, and core unit. While the combat power-related operational readiness (OR) measures satisfy many of the conditions, the IDA team constructed and used a measure similar to the OR measure, called "fault spell duration," which better satisfies condition 3 because it allows NMC events that span reporting periods to be analyzed as a single event, preserving information about contiguous maintenance events. Fault spell duration also allows distinct maintenance events within reporting periods also to be analyzed as distinct events. Lastly, fault spell duration contains information on the type of maintenance, whereas OR measures do not. Fault spell duration is explained first, followed by discussion of other possible measures.

A fault is a helicopter maintenance or inspection event. The IDA team focused on faults that result in an NMC status. Multiple faults can be open for the same helicopter at any given time. Thus, a change in fault duration for any given fault may or may not affect total NMC time over a given period. To account for this, the IDA team aggregated faults for a given aircraft into contiguous *fault spells*, consisting of an unbroken set of overlapping faults. The construction of fault spells is presented in Section 3.B. Fault spell duration has a stronger causal connection to the number of MilTech mechanics than reported OR measures, but the data required to compute fault spell duration are only reliably reported for H-60 helicopters. Thus, condition 5 does not hold for all other aircraft. Reductions in fault spell duration have the added benefit of being equivalent to increases in MC time.

OR readiness measures are reported as total hours or the percentage of total hours per month that a tail number (i.e., serial number) is in a certain readiness status. Figure 12 illustrates the two main measures of MC or NMC. MC is comprised of partially mission capable (PMC) and fully mission capable (FMC). NMC time is partitioned by not mission capable due to supply (NMCS) and not mission capable due to maintenance (NMCM). Likewise, PMC time is partitioned by partially mission capable due to supply (PMCS) and partially mission capable due to maintenance (PMCM). During numerous engagements, the IDA team was informed that while FMC, PMC, and NMC are accurately reported, the split between supply and maintenance for PMC (PMCM/PMCS) and NMC (NMCM/NMCS) is not consistently reported throughout the ARNG, violating condition 4 and thus were not considered for measures of effectiveness.[33]

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32 Department of the Army, *Headquarters: Army Aviation Maintenance*, Army Technique Publication No. ATP 3-04.7 (Washington, DC, Headquarters Department of the Army, Sept 2017),

33 The implementation of Aircraft Notebook (ACN) will automate the reporting NMCS and thus provide reliable reporting of NMCS and NMCM.

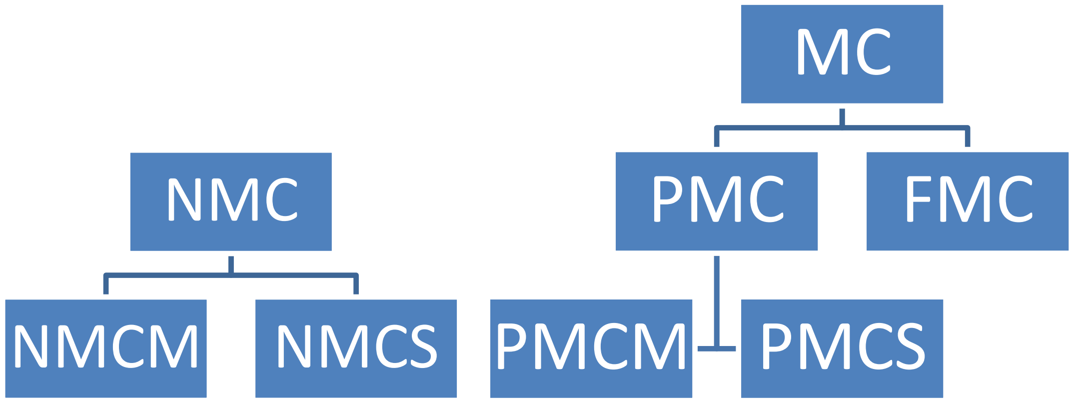

Figure 12. OR measures

FMC status is when a helicopter can perform all requirements of its mission-design series (MDS) and meet the system/subsystem operational requirements as specified in AR 700-138.[34] A helicopter is in PMC status when it does not have certain required subsystems or quantities of equipment. When reporting as PMC, a helicopter is capable of performing a limited number of missions or is limited in the performance of missions. A helicopter is in NMC status when critical subsystems are non-operational.

NMC time is a function of how long it takes to complete helicopter maintenance. Thus, one could hypothesize that an increase in MilTech mechanics would reduce NMC time to the extent that MilTech mechanics contribute to completion of maintenance. However, using fault spell duration rather than NMC time (from OR measures) as an outcome measure allows NMC events that span a month-end to be analyzed as a single event. For example, Figure 12 depicts two calendar months containing three different fault spells for two helicopters, represented by the blue solid (Helicopter A) and green solid (Helicopter B) lines. Both helicopters report 45% and 35% NMC OR measures for months one and two, respectively. However, Helicopter A experiences two different fault spells, while Helicopter B has only one fault spell. Suppose an increase in the number of MilTech mechanics during the first month reduces each fault spell length in that month as shown by the dashed lines. How is this impact captured by NMC OR measures versus fault spell duration? With NMC OR measures, the effect of the increase in MilTech mechanics is appropriately attributed to month 1 for Helicopter A. However, the effect is incorrectly attributed to month 2 for Helicopter B. With fault spell duration, the NMC time for Helicopter B is treated as a contiguous event and the effect is appropriately attributed. Thus, NMC OR measures violate condition 3.[35]

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[34] Department of the Army, "Army Logistics Readiness and Sustainability" Army Regulation 700–138 (Washington, DC: Headquarters Department of the Army,143, http://asktop.net/wp/download/3/r700_138.pdf.

[35] An alternative analysis using OR measures was briefly pursued and is mentioned in the Alternative Specifications and Robustness Checks section.

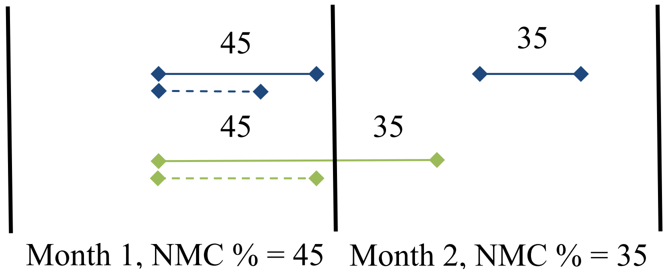

Figure 13. Contiguous vs. Separate Maintenance Events, OR Example

Another potential outcome measure is *bank time* or fleet bank time (see ATP 3-04.7).[36] Bank time for an individual helicopter is defined as the number of remaining flight hours before the next phase maintenance. Fleet bank time is defined as the sum of bank times for helicopters in a given customer Unit Identification Code (UIC) and model family. Bank time determines prioritization of labor on a day-to-day basis. Since phase maintenance causes the helicopter to be down for a long period, the goal of production control is to maintain a consistent distribution of bank times over tail numbers for a given model family to reduce unexpected non-availabilities of helicopters. However, bank time is at best indirectly related to MilTech mechanic headcounts, and is difficult to compute from available data, violating conditions 2 and 3.

We thus chose fault spell duration as the readiness-relevant outcome in this analysis because it best satisfies all six conditions.

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36 Department of the Army, *Headquarters: Army Aviation Maintenance*, Army Technique Publication No. ATP 3-04.7 (Washington, DC, Headquarters Department of the Army, Sept 2017),

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3. Data

This chapter describes the eight data sources used to conduct this analysis, including the information used, how data were combined, and how we handled missing and incorrect data. The period of analysis is from September 16, 2010 to September 15, 2019 (i.e., fiscal years 2011 to 2019). Tail number (i.e., serial number) identifies individual helicopters.

A. Sources

Data for this project included information on helicopter readiness, helicopter faults, MilTechs, uniformed ARNG members (hereafter, “uniformed personnel”), personnel assigned as active duty for operation support (ADOS), traveling maintenance and contractor support teams, parts, and facilities.

1. Readiness Data

In accordance with AR 700-138, each AASF reports monthly helicopter inventory, status, and flight hours via DA Form 1352. Each report covers the period from the 16th of a given month to the 15th of the subsequent month. The ARNG Aviation and Safety Division provided the IDA team with monthly consolidated 1352 forms for every ARNG helicopter tail number. For each tail number and month, the readiness information provided included hours in FMC, PMC, NMC, depot maintenance, and the percent of the month spent in each of those statuses.[37] More specific information was provided for NMCS, NMCM, PMCS, PMCM, and whether the depot maintenance occurred at a TASM-G or AASF (where applicable). Helicopter-specific information includes model, status, hours flown that month, total airframe hours, servicing maintenance facility identifier, and owning customer UIC.

The readiness data covered 183,000 helicopter months, of which 66% are for H-60 helicopters,[38] in fiscal years 2011 to 2019. We removed records with missing tail numbers or zero possible hours. This analysis focuses on maintenance at AASFs. Therefore, any maintenance not occurring at an AASF was removed or accounted for. Even though a helicopter may not have been physically located at the AASF, it might be reported at an AASF in the readiness data. Therefore,

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[37] The IDA team did not use the supplied NMC percent variable due to inconsistencies that were identified. Instead, the IDA team constructed NMC percent by dividing NMC hours by possible hours.

[38] These counts exclude October 2010 and February 2012, which were entirely unavailable.

we removed tail number months where the helicopter was deployed, mobilized, crashed, in reset, in a Black Hawk exchange sales team program (BEST) status, or at a TASM-G.[39]

2. Fault Data

The U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) provided the IDA team with ARNG helicopter fault data. A fault represents a unique inspection or maintenance event performed on a helicopter, initiated by opening a new DA Form 2408-13-1, known simply as "13 dash 1." Due to inconsistent reporting requirements over time, only H-60 helicopter models have consistently reported 13-1 forms over the period of analysis; thus we excluded all other models. The analysis set includes faults opened between September 16, 2010 and September 15, 2019[40]; faults in this timeframe close in December 2019 at latest. We dropped faults with no end date, which comprised approximately 1.2% of total faults. These data contained 6.2 million faults, including 1.2 million NMC faults.

Each 13-1 contains the helicopter tail number, opening date and time, closing date and time, an indicator for phase maintenance, a free-text fault description field, corrected work unit code (CWUC; i.e., the system code describing the part of the aircraft the maintenance issue impacted), a status field indicating the severity of the fault, and aircraft flight hours.[41] We restrict the analysis to faults with a red X status and pertain to the airframe itself (identified by the system code) to ensure the helicopter is in an NMC status, which is approximately 20% of faults.[42] We also

[39] The status field identifies deployed, mobilized, crashed, reset, BEST, and depot maintenance. Unfortunately, while the status field is present in each year of data, the IDA team was told by the ARNG aviation division that reporting of the field could not be trusted for every year prior to FY2018. The IDA team compared the counts of UH-60 Black Hawk helicopter pilots from the UP data to the counts of UH-60 Black Hawk helicopters from the readiness data and found concurrence between the two. Thus, the team assumes that the deployed status in the readiness data was accurately reported.

To augment the status field, the IDA team received reset data containing individual helicopter start and end dates covering the period of analysis. The IDA team used the union of the status field and the reset data to identify helicopters in reset.

Depot maintenance can occur at AASFs or TASM-Gs, but the tail number can be reported at the AASF. Depot maintenance events occurring at the TASM-G do not count against the readiness for the tail number. This fact can be used to identify depot maintenance that occurs at the AASF and depot maintenance that occurs at the TASM-G. We remove tail number months where the helicopter is located at the TASM-G.

[40] Given the way we construct fault spells, to ensure that no spells included potentially time-overlapping faults that began prior to September 16, 2010, we initially keep faults that begin on or after January 1, 2010, to identify and drop these spells. Construction of fault spells is discussed later.

[41] Specifically, we used the field for aircraft flight hours at the beginning of the fault ("ACHRS"), and if this was not available fault end flight hours ("CACHRS").

[42] This ensures the helicopter is in a non-flyable status. A red X 13-1 fault can be open for a helicopter part, component, or subsystem that is swapped out for an available one on the shelf, through a controlled exchange, by a replacement received from the TASM-G, or by borrowing from another AASF.

removed faults with incomplete information on tail number, begin or end date, an end date preceding the start date, and with a duration of zero minutes.

Feature engineering: fault type text analytics

The fault data contain little machine-understandable information regarding the specific type of maintenance required for each fault record. Although the CWUC code offers some insight, the field had little variation, and over one-quarter of records is missing this field. Information on the type of fault can increase the precision of the estimates and possibly reduce bias as well. Therefore, we assigned faults to a topic using a latent Dirichlet allocation (LDA) model on the free-text fault description field. LDA is a natural language processing (NLP) model that probabilistically identifies unobserved "topics" (which will ideally correspond to the type of fault) based on words that frequently occur together in the same document.[43,44] The LDA model maps faults to each of the identified topics with varying probabilities. Each 13-1 record is assigned to the topic with the highest estimated probability (called the *dominant topic*).

The LDA algorithm requires the researcher to choose the number of topics. Specifying too few topics may result in classifying two different types of faults as the same. Conversely, too many topics may result in repetitive topics with little differential information (introducing noise). To determine the optimal number of topics, a series of LDA models are fit (using a five percent panel sample of tail numbers), with the number of topics ranging from 5 to 70. The models are then compared using information criteria that balance the amount of information explained against the complexity of the model—a mathematical representation of Occam's razor.[45] These criteria suggest that the optimal number of topics is 40.

Prior to applying the LDA algorithm, the free text is preprocessed in several ways. Uninformative common words (known as "stop words") such as prepositions, articles, and conjunctions are removed entirely. The text is then lemmatized (i.e., convert verbs to present tense), and stemmed (e.g., disbanded becomes disband). In addition, two and three word phrases are combined into one word. [46]

Table 2 displays examples of original fault descriptions contained in the data (far left column). The middle left column presents the preprocessed versions of these same descriptions.

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[43] Blei, D. M., Ng, A. Y., & Jordan, M. I., "Latent Dirichlet allocation," *Journal of Machine Learning Research*, *3* (Microtome Publishing, January 2003), 993-1022.

[44] The LDA is an unsupervised machine learning model, which is a class of models designed to handle data where no known truth labels exist. In this case, a truth label is a topic that must be inferred.

[45] The information criteria used were the Akaike information criterion (AIC) and Bayesian information criterion (BIC). They were compared on the econometric model presented in Section 4.B.

[46] We also restrict to words present in at least 30 different fault descriptions to remove sparse (and potentially misspelled) words. Conversely, extremely common words (i.e., those that appear in more than 800 fault descriptions) are also dropped to remove words with low information (e.g., "a," "the," "but," "not, "to," "is," "and").

The middle-right column displays the top four keywords of each fault description's dominant topic. Many fault descriptions belong to a topic so the topic keywords may contain terms not found in the processed fault description. The far right column displays the topic number the fault belongs to.

Table 2. LDA Examples

Original	Processed	Keywords	Topic
#1 HYD PUMP RETURN LINE QD NOT TQ, CAN BE SPIN FREELY BY HAND	pump, line, freeli, hyd, return, spin	light, pump, hyd, boost	22
INBOARD SEAL OF RED TAIL ROTOR BLADE BOOT HAD DISBONDED AND IS SEPERATING FROM ZIP TIE	boot, seal, tail, zip, seper, rotor, tie, disbond, blade, inboard	tail, rotor, deic, hdwr	8
BLOT ON TAIL ROTOR SERVO LINK CONNECTED TO PUSH ROD HAS IMPROPERLY INSTALLED COTTER PIN	tail, rod, servo, connect, instal, rotor, cotter, pin, push, link, improp	tail, rotor, deic, hdwr	12

3. MilTech Data

The NGB-J1-TNH provided administrative data from the Defense Civilian Personnel Data System (DCPDS) at the person-month level on all MilTechs in the ARNG for the full period of analysis. MilTechs comprise the majority of FTS positions employed to maintain the ARNG fleet. While dual-status MilTechs are required to maintain ARNG membership to retain their full-time occupations, the MilTech data only provides information on these individuals' full-time civilian ARNG occupations. Over the period of analysis, the ARNG employed 633,000 person-months of MilTech labor at flight facilities, 49% percent of which were helicopter maintainers.

Of primary interest to this analysis is the four-digit occupational series of each MilTech.[47] The occupational series and job titles are used to classify MilTechs as helicopter mechanics. An occupational series of 8852 corresponds to aircraft mechanics (including H-60 helicopter mechanics). Backshop maintainers, who are differentiated from direct mechanics in our analysis, specialize in electronics, sheet metal, or other back-shop features of a typical AASF. Maintenance test pilots and quality assurance specialists are also included as backshop personnel due to their significant impact on the maintenance process.

The MilTech data include a UIC field that indicates the unit in which the individual performs their full-time duties. The corresponding "unit name" field is used to identify the AASF where

[47] U.S. Office of Personnel Management, "Handbook of Occupational Groups and Families," (Washington, DC), https://www.opm.gov/policy-data-oversight/classification-qualifications/classifying-general-schedule-positions/occupationalhandbook.pdf.

each individual is employed. ARNG membership may require MilTechs to leave their full-time roles for a specific amount of time to fulfill military obligations, such as training, mobilizations, and deployments. Therefore, we exclude maintainers not present in their full-time position.[48]

A number of other administrative fields are contained in the MilTech data, including information on pay plans, pay rates, veterans' preference, appointment authorities, and supervisory statuses. This analysis primarily utilized occupational series, job titles, unit identifiers, and pay statues, which were all both well populated and salient to our analysis. Future work could attempt to make use of the remaining information.

4. Uniformed Personnel Data

ARNG G1-HRM provided data on all uniformed personnel (UP) in the ARNG for the period of analysis from the Reserve Component Manpower System–Guard (RCMS-G). The UP data is measured at the person-month level and provides information on the military role of each individual. The UP data is used to identify deployments of AASF mechanics and to capture additional characteristics of customer units that may impact the readiness and maintenance of their helicopters.[49] Finally, even though the UP data show when individuals at customer units are deployed, helicopter deployments are not captured. Units often deploy with helicopters not belonging to their unit, either because other helicopters are already available in theater or because other helicopters were selected at the pre-deployment mobilization station.

For each person-month, the UP data provides binary indicators of whether an individual was mobilized or deployed, as well as each individual's drilling UIC, years of service, MOS (primary, secondary, position, and duty), position title, and rank. We classify 6-digit UIC-level customer units as deployed for months in which at least 70% of their personnel are deployed. Because drilling soldiers may perform maintenance during drill weekends and training events, we also calculate the number of drilling maintainers in an aviation maintenance-related primary MOS for each customer unit month.

5. Active Duty for Operational Support–Reserve Component

ARNG G1-HRM provided data on all Active Duty for Operational Support–Reserve Component (ADOS) orders in the ARNG for the period of analysis. This data is at the ADOS order level. Each order is assigned to a single individual and contains a start and end date, in addition to a duty code that broadly describes the reason for the order.

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48 The fact that a MilTech is reported at a particular AASF in a given month in the data does not necessarily mean that he or she actually worked there during that time. A pay status field is used to identify which MilTechs were present for work each month and which ones were absent (e.g., due to a military duty). The pay status field only shows whether a MilTech is present. It does not indicate the specific reason (e.g., deployment) for an absence.

49 Customer UICs are identified in the readiness data and then matched to UICs in the UP data.

The ADOS data tracks the UIC of the ARNG drilling member's home unit, which may not be the unit the individual is supporting for the ADOS order. Thus, the ADOS data does not identify which orders support an AASF. During site visits, the IDA team was informed that many soldiers on ADOS orders support the customer unit and not the AASF. Therefore, to isolate the individuals on ADOS orders supporting an AASF, we remove all individuals except those on an aviation maintenance-related primary MOS who drill at a customer unit of an AASF.[50,51] Further, ADOS order codes that clearly do not support maintenance were removed.[52] Maintenance-related ADOS tours are typically short, with a median duration of just 5 days.

For a given AASF, we compute the total number of ADOS person-months of personnel supporting the AASF. Since the data includes the start and end date of each order, we first calculate the fraction of each the month covered, and then sum these fractions across all ADOS orders at the AASF-month level.

6. Traveling Teams and Contractor Data

The ARNG G-1 Full-Time Support Division provided data on traveling maintainer teams from the Aviation Roundout Maintenance Management Information System. This database records maintenance events performed by TASM-G personnel, including traveling teams and contractors. These data were collected during an unrelated manpower study and do not cover the full period of analysis. The unit of observation is a maintenance action. Each action includes the badge ID of the individual who performed the work, the start and end time, and some general descriptions of the work completed. In addition, the data includes the UIC of the TASM-G in which the individual is assigned and the UIC of the maintenance facility where the work is performed.

We restrict these data to maintenance actions performed by contractors and individuals on a traveling team in support of an AASF. To measure the amount contractor and traveling team support provided to each AASF in each month, the durations of all maintenance actions are aggregated to person-hours for analysis.

7. Parts Data

The ARNG Aviation and Safety Division provided data from GCSS-Army on all equipment parts ordered by aviation maintenance facilities during the period of analysis. Each record in the data is a unique part order. The data include the date when a part request is funded and becomes a

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[50] We classify each of the following as an aviation maintenance-related MOS: 09W, 15A, 15B, 15D, 15F, 15G, 15H, 15J, 15N, 15R, 15S, 15T, 15U, 15Y, 91E.

[51] If a soldier on an ADOS order drills at a customer unit that has helicopters at multiple facilities, the soldier is assigned to the facility that has the majority of that unit's helicopters.

[52] Subject matter experts in the ARNG G1 provided a list of maintenance-related type of duty codes by removing all duty codes that clearly do not support an AASF (e.g., Honor Guard, resilience training, and so forth).

part order. The data also provides the expected delivery date at the time the parts request becomes a part order. Note that these are not necessarily the dates when a part request is made, nor when the part is delivered. However, the provided dates can be used as an approximation for the time between request and delivery. The data also contains the name of the part, the quantity of parts, the purchase price, the vendor that fulfilled the order, the helicopter model in which the part is required, and the UIC of the facility that submitted the order.

The IDA team used parts data to control for fluctuations in a facility's inventory, to compensate for not being able to separate NMC time into NMCM and NMCS. That is, when a facility has a relatively large number of outstanding parts orders, it is more likely that the helicopters at this facility will have relatively more NMCS time, which is less likely to be related to the number of maintainers. As a result, the individual parts orders are aggregated into both the number of outstanding parts orders and the number of days spent waiting on all parts orders for each facility and month for analysis.

8. Facility Identifiers

The readiness and MilTech data provide different identifiers for aviation maintenance facilities. The readiness data includes a facility ID that includes a two-digit state abbreviation and a facility number within that state. For instance, the state of Connecticut has two aviation maintenance facilities that are identified in the readiness data as CT1 and CT2. In the MilTech data, the state, UIC, and unit name fields identify maintenance facilities. Neither the readiness nor MilTech contain sufficient data to link, for example, the identifier CT1 in the readiness data to its corresponding UIC in the MilTech data.

To associate the facility ID field in the readiness data to facility UICs in the MilTech data, the ARNG aviation facilities coordinator provided data on all aviation maintenance facilities in the ARNG. This data includes a unique facility ID, UIC, and facility type (e.g., AASF, TASM-G, etc.) for every facility and provides the ability to create a common facility identifier by which the readiness and MilTech data can be merged. That is, the facility data provides the ability to link CT1 in the readiness data to the UIC in the MilTech data. The facility type field is used to subset the readiness data on helicopters reported at an AASF—not other facilities, such as a TASM-G or an AATS. The data also includes facility features such as date of construction and square footage, but those fields are not used because facility fixed effects are used in this analysis.

B. Scoping – Fault Spells

A single helicopter often has multiple red X faults open at the same time. Therefore, the total timespan covered by overlapping faults—not the individual faults themselves—determine helicopter NMC time. Moreover, because closing one fault can depend on first completing another (potentially overlapping) fault, it is inappropriate to model faults individually. We, therefore, combine overlapping faults into "fault spells," which span the full maintenance process from when a helicopter enters a non-flyable status to when it becomes flyable again. Also contributing to our choice to combine faults into fault spells is that on-site interviews indicated that labor allocation decisions are made at the tail number level and not at the fault level.

To construct fault spells, we group faults according to tail number and start and end time, using the minimum and maximum time of each grouping to represent the spell start and end time, respectively. Importantly, spell boundaries are identified with temporal gaps of greater than 30 minutes between the time when all faults for a given tail number have been closed and the time when one or more new faults are opened for the same tail number.[53] Figure 13 presents the number of (NMC) fault spells for H-60 helicopters in the ARNG over time, by start date. Fault spell duration is constructed as the difference (in minutes) between the end and the start of the spell. Figure 14 compares NMC time as measured by monthly readiness reports versus NMC time as measured by fault spell duration, and illustrates that their difference is centered at zero, with equivalence on average. Thus, it is reasonable to use fault spell duration as a measure of NMC.

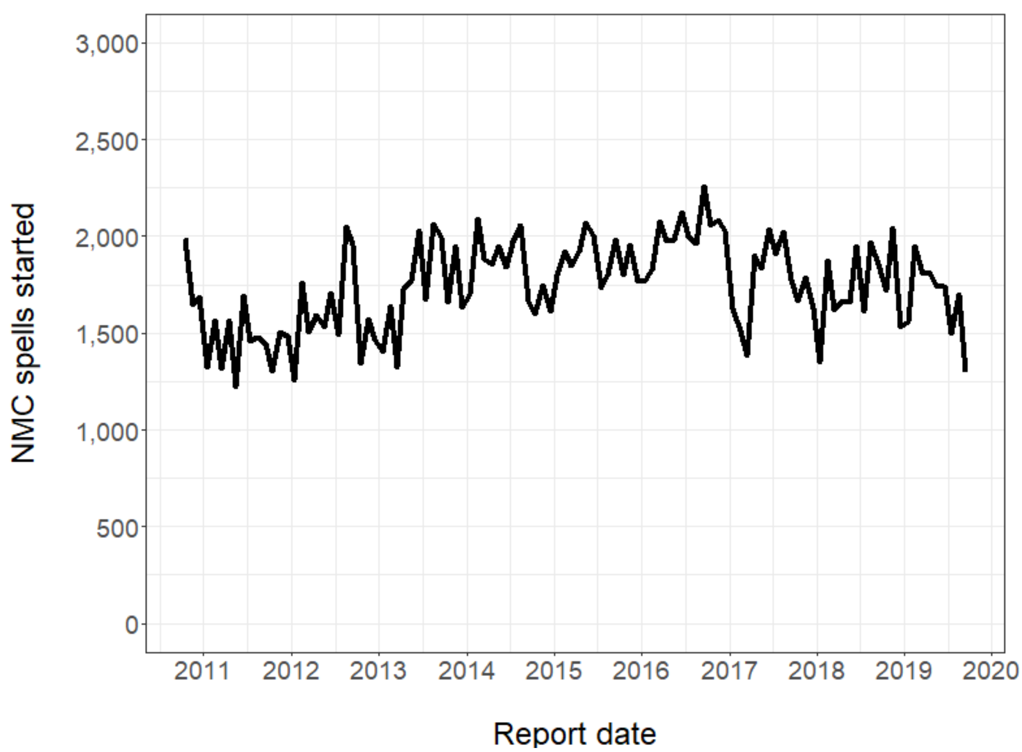

Figure 14. NMC Spell Starts

53 Specifically, the algorithm: 1) rounds datetimes to the nearest hour; 2) drops duplicates on tail number, start datetime, and end datetime; 3) fills (hourly) gaps between start datetime and end datetime; and 4) removes duplicates (other faults that occurred on this same tail number during this hour). Temporal gaps of less than 30 minutes are combined because after a fault closes, a helicopter can still be effectively NMC. This is due to further repairs being required but a new fault has not been opened up yet in the system. The 30-minute threshold was informed by AASF staff during site visits.

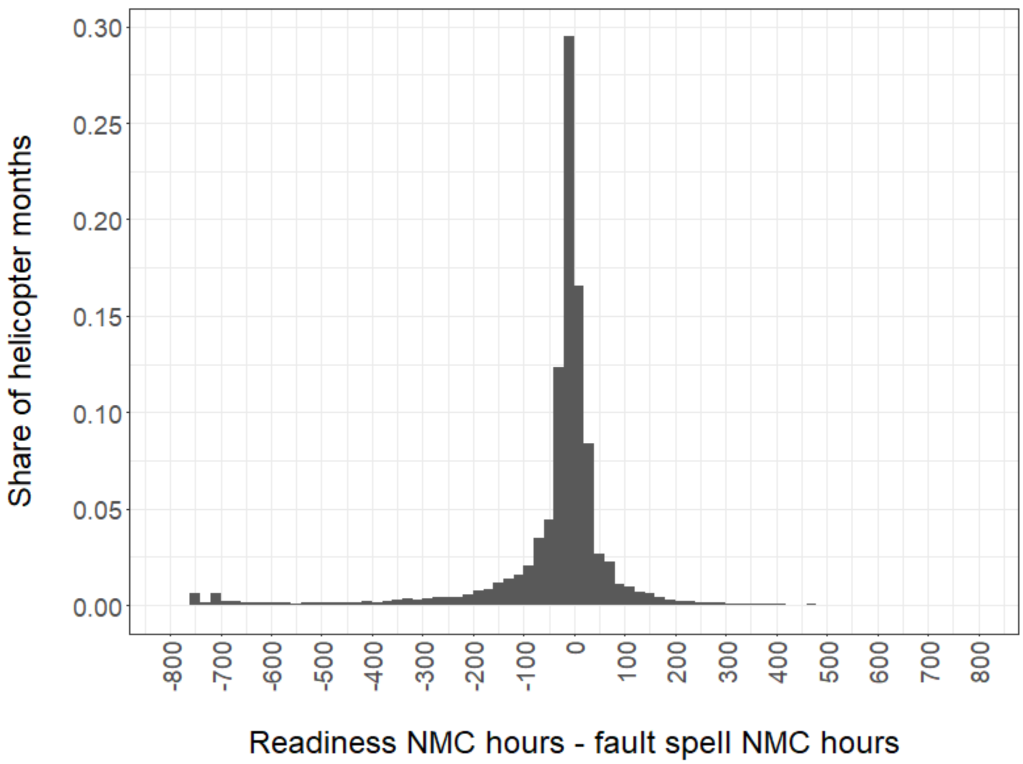

Figure 15. Readiness NMC vs. Fault Spell NMC

Fault-specific information is then aggregated up to the spell level. If any fault within a spell is flagged as phase maintenance, the entire spell is considered a phase spell. We retain or calculate information on the number of faults opened (and closed) during the spell, the number of distinct LDA-dominant topics across all faults in the spell, the number of unique CWUC codes across all faults, the most common dominant-LDA topic, and the day of the week on which the spell began.

Lastly, spells are included in the analysis only if the tail number is present in the readiness data at the same AASF for the entire duration of the spell. This restriction reduced the sample of spells by approximately 4 percent. Many of the eliminated spells featured extremely long durations (e.g., greater than 365 days). Closer inspection showed that these extreme durations corresponded with model block upgrades from the UH-60L to the UH-60M model, which is an acquisition action rather than a maintenance action.

C. Merge Process

We combined the data from these sources into a single dataset to estimate the econometric model. The final dataset is called the *regression set*. To arrive at the regression set, we performed a number of sequential merges and restrictions as shown in Figure 15. The goal is to connect the fault data with the personnel data and other data sets. The readiness and facility datasets are used as intermediaries to link all data sets. First, the facility identifiers are merged onto the readiness and MilTech data, which allows the readiness data to be linked to the MilTech data. Then, the variables extracted from the traveling teams and parts data are merged onto the readiness data by facility ID and month. The readiness data is then restricted to helicopter months located at an AASF. Then, the readiness data and the UP data are merged by customer UIC and month. Next, the readiness data is merged with the MilTech data by facility ID and month, and the intersection is retained. Finally, analysis can be performed on the resulting dataset that is described later in this paper.

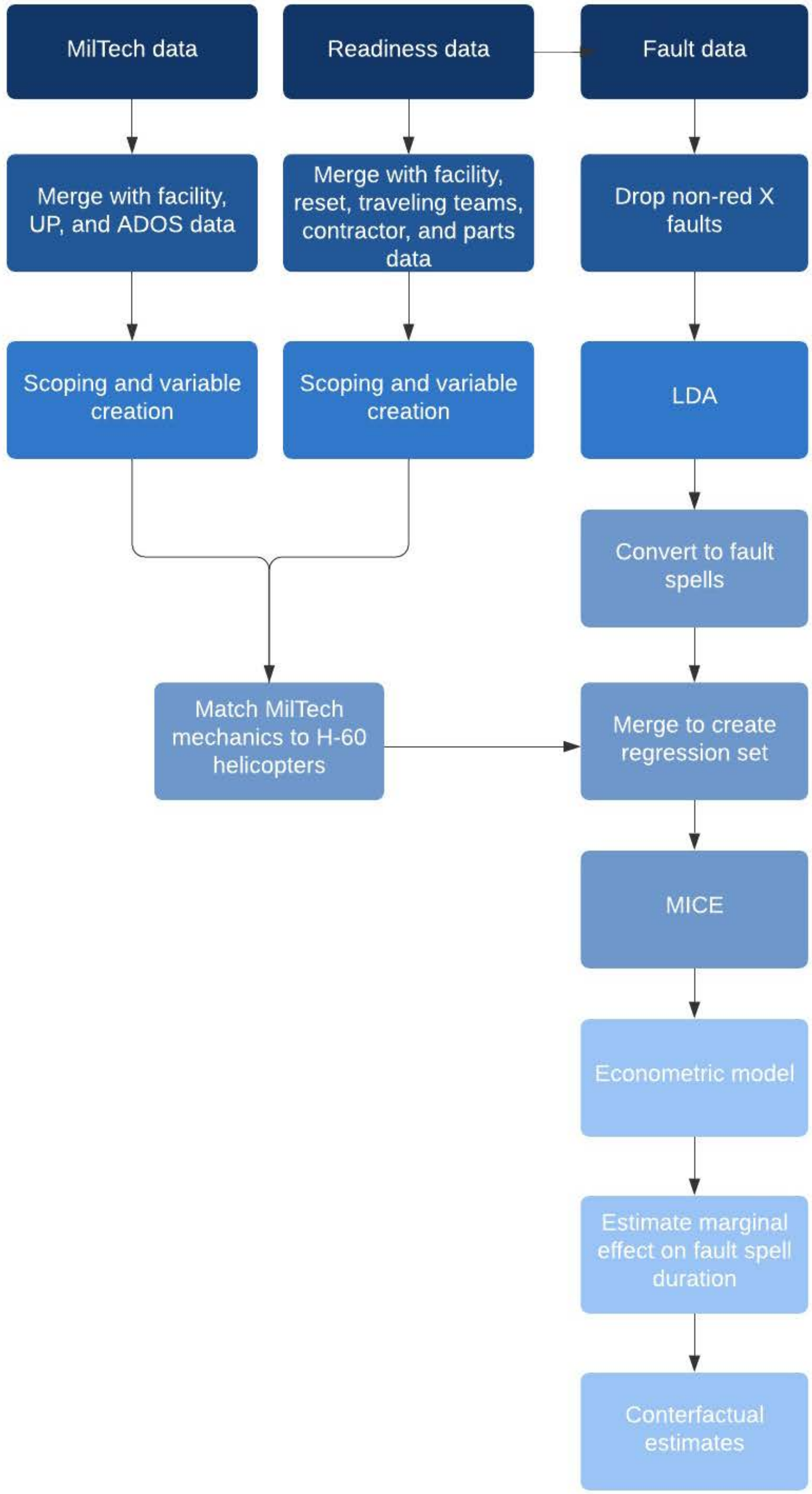

Figure 16. Analysis Flowchart

Table 3 shows how the population of MilTechs changes across the various merges. The second column describes the population of MilTechs at all ARNG flight facilities, while the third column shows those retained after the merge with the readiness data. Finally, the resulting readiness data is subset on helicopters that are not deployed and then merged with fault spells by serial number and month.[54] The intersection of this merge is the regression set, as presented in the last column of Table 3. The reduction from the second to third columns is primarily due to removing specialized training facilities, TASM-Gs, and other non-AASFs. The reduction from the third to the fourth column is primarily due to removing facilities with no H-60 helicopters and helicopters in a deployed, mobilized, best, crash, depot, or reset status.

Table 3. Personnel Reconciliation

	Flight facilities	Intersection with readiness	Nondeployed	Intersection with faults
MilTech man-months	633,170	541,706	535,949	423,580
MilTech mechanics	175,233	156,026	155,258	124,724
MilTech backshop maintainers	135,241	105,487	104,873	80,744
TempTech mechanics	13,453	11,719	11,680	9,076
TempTech backshop maintainers	5,914	3,822	3,781	2,882
ADOS mechanic man-months	4,320	4,260	4,241	3,514
ADOS backshop maintainer man-months	2,009	1,970	1,962	1,565
Number of facilities	104	90	90	77
Mean MilTechs per facility	57.6	57.8	58.0	58.3
Mean MilTech mechanics per facility	20.8	21.7	21.8	22.2
Mean MilTech backshop maintainers per facility	15.5	14.1	14.2	13.8

Table 4 shows how the populations of faults and fault spells change across merges and aggregations. The second column shows the population of all faults. The second column to the third column shows how the population of faults reduces when non-NMC faults are excluded. The third column to the fourth column shows how the population changes as NMC faults are combined into fault spells. As one would expect, there is a large (75%) decrease as faults are combined into

[54] Faults spells are merged on the month that the fault spell beings.

spells. However, the median duration decreased 87%, when one might expect it to increase. This is partially due to phase maintenance generating many faults at initiation and it taking a long time to resolve the individual faults.[55] The fourth column to the fifth column shows the final reduction as the fault spells are merged into the regression set. The sample reduction from this last merge is primarily due to dropping faults for helicopters that do not belong to the ARNG, or that were in transition between facilities or statuses.

Table 4. Fault Reconciliation

	All faults	NMC faults	NMC faults collapsed into spells	Regression set
Number of faults/spells	6,238,663	1,184,783	295,719	190,342
Number of helicopters	1,249	1,249	1,248	1,199
Median duration (minutes)	4,294	1,741	230	225

D. Missing Data

There were many instances of missing data in the dataset, most of which were due to incomplete collection. There were 28 covariates with missing data, which are presented in Table 5. The covariates are listed in increasing order of completeness. Man hours worked by traveling teams at the AASF has a low rate of completeness, 36.4%, which is due to the data only being collected for a brief period of time at each of the four TASM-Gs for a manpower study. The next several variables are deployment or mobilization indicators that are missing due to censoring on right end of our data and an incomplete merge. For example, if the data ends in September 2019 and there was no deployment then in August 2019, we cannot determine if there was a deployment in 12 months or less. The rest of the covariates with missing data are due to incomplete merges where one dataset lacked a corresponding entry in a different dataset during a merge. The missing data is imputed with multiple imputation using chained equations (MICE) to improve statistical power and causal and econometric validity discussed in section 4.C.

[55] When a phase maintenance begins, many faults are opened (34 faults on average) but cannot be addressed or closed until far into the phase maintenance. Thus, a phase fault spell is constructed from many long and overlapping individual faults. This causes the distribution of fault durations to have a large mass for long faults. When those phase faults are collapsed into a single phase fault spell, it produces a distribution of fault spells durations with a low mass for long durations.

Table 5. Missing Data

Variable	Percent complete
Man hours worked by traveling teams at the AASF	36.40%
Indicator for a customer unit mobilization or deployment in 12 months or less	83.40%
Indicator for a customer unit mobilization or deployment in 6 months or less	88.20%
Fraction of AASF's maintainers mobilized or deployed in 12 months	90.10%
Indicator for a customer unit mobilization or deployment in 3 months or less	90.70%
Indicator for a customer unit mobilization or deployment in 1 month or less	92.30%
Number of H-60 helicopter pilots at the customer unit	93.00%
Number of mechanics at the customer unit	93.00%
Number of backshop maintainers at the customer unit	93.00%
Number of H-60 helicopter pilots in the state in the prior fiscal year	93.00%
Fraction of AASF's maintainers mobilized or deployed in 6 months	95.80%
Mean airframe hours of AASF's helicopters in the prior month	96.30%
Helicopter prior month hours flown	96.30%
Helicopter prior month airframe hours	96.30%
Mean helicopter hours flown in prior 3 months	97.10%
Mean hours flown of AASF's helicopters in the prior month	97.20%
Number of outstanding parts orders for H-60 helicopters	97.80%
Number of outstanding parts orders, excluding H-60 helicopter orders	97.80%
Total number of days spent waiting for outstanding H-60 helicopter parts orders	97.80%
Total number of days spent waiting for outstanding parts orders, excluding H-60 helicopter orders	97.80%
Number of UH-72 Lakotas at the AASF	98.00%
Indicator for any fixed wing aircraft at the AASF	98.00%
Indicator for an helicopter deployment in 1 month or less	98.00%
Indicator for an helicopter deployment in 3 month or less	98.00%
Indicator for an helicopter deployment in 6 month or less	98.00%
Indicator for an helicopter deployment in 12 month or less	98.00%
Fraction of AASF's maintainers mobilized or deployed in 3 months	98.40%
Mean hours flown of AASF's helicopters in prior 3 months	98.90%

E. Variable summaries

Table 6 presents mean, median, and standard deviation of variables used in the regression model. The first variable, the natural logarithm of fault spell duration, is the outcome variable. The third variable, MilTech mechanics, is the covariate of interest. The first column of the table shows the level at which each variable varies.

Table 6. Variable Summaries

Level of Variation	Variable	Mean	Median	Std. Dev.
Fault spell	Natural logarithm of fault spell duration	5.4	5.4	2.6
None	Intercept	1	1	0
AASF month	MilTech mechanics	19.2	17	11
	MilTech backshop maintainers	12.2	11	7.3
	TempTech mechanics	1.3	0	2
	TempTech backshop maintainers	0.4	0	0.9
	ADOS mechanics	0.6	0	1.4
	ADOS backshop maintainers	0.2	0	0.6
	Man hours worked by traveling teams at the AASF	129	0	420
	MilTech mechanics mobilized, deployed, or on leave	3.7	2	4.9
	MilTech backshop maintainers mobilized, deployed, or on leave	2.2	1	3
	Fraction of AASF maintainers mobilized or deployed in current month	0	0	0.1
	Fraction of AASF maintainers mobilized or deployed in 1 month	0	0	0.1
	Fraction of AASF maintainers mobilized or deployed in 3 months	0.1	0	0.1
	Fraction of AASF maintainers mobilized or deployed in 6 months	0.1	0	0.1
	Fraction of AASF maintainers mobilized or deployed in 12 months	0.1	0	0.1
	Mean NMC% of AASF's H-60 helicopters in the prior month	0.3	0.3	0.2
	Mean NMC% of AASF's H-60 helicopters in the prior 3 months	0.3	0.3	0.1
	Mean NMC% of AASF's AH-64, CH-47, and OH-58 helicopters in the prior month	0.1	0	0.2
	Mean NMC% of AASF's AH-64, CH-47, and OH-58 helicopters in the prior 3 months	0.1	0	0.1
	Mean hours flown of AASF's helicopters in the prior month, excluding UH-72 Lakotas	13.4	12.7	5.9
	Mean hours flown of AASF's helicopters in the prior 3 months, excluding UH-72 Lakotas	187	160	123

Level of Variation	Variable	Mean	Median	Std. Dev.
	Mean airframe hours of AASF's helicopters in the prior month, excluding UH-72 Lakotas	3,082	3,108	1,736
	Number of H-60 helicopters at the AASF	12	11	5.3
	Number of AH-64, CH-47, and OH-58 helicopters at the AASF	2.6	0	5
	Number of UH-72 Lakotas at the AASF	1.7	0	2.2
	Indicator for any fixed wing aircraft at the AASF	0.5	0	0.5
	Number of outstanding parts orders for H-60 helicopters	0.8	0	2.2
	Number of outstanding parts orders, excluding H-60 helicopter orders	1.9	0	5.8
	Total number of days spent waiting for outstanding H-60 helicopter parts orders	45.5	0	254
	Total number of days spent waiting for outstanding parts orders, excluding H-60 helicopter orders	103	0	279
Customer unit month	Number of H-60 helicopter pilots at the customer unit	11.5	12	5.5
	Number of mechanics at the customer unit	15.2	16	5.6
	Number of backshop maintainers at the customer unit	3	3	2.4
	Indicator for a customer unit mobilization or deployment in 1 month or less	0.1	0	0.3
	Indicator for a customer unit mobilization or deployment in 3 months or less	0.1	0	0.3
	Indicator for a customer unit mobilization or deployment in 6 months or less	0.1	0	0.4
	Indicator for a customer unit mobilization or deployment in 12 months or less	0.2	0	0.4
Helicopter month	Indicator for an helicopter deployment in 1 month or less	0	0	0.1
	Indicator for an helicopter deployment in 3 month or less	0	0	0.2
	Indicator for an helicopter deployment in 6 month or less	0	0	0.2
	Indicator for an helicopter deployment in 12 month or less	0.1	0	0.3
	Helicopter prior month hours flown	15	13	12.5
	Mean aircraft hours flown in prior 3 months	14.2	13	9.1
	Helicopter prior month airframe hours	3,332	4,092	2,426

Level of Variation	Variable	Mean	Median	Std. Dev.
	Indicator for HH-60A Pave Hawk	0	0	0
	Indicator for HH-60L Pave Hawk	0	0	0.1
	Indicator for HH-60M Pave Hawk	0.1	0	0.2
	Indicator for UH-60L Black Hawk helicopter	0.4	0	0.5
	Indicator for UH-60M Black Hawk helicopter	0.1	0	0.3
Fault spell	Number of faults in spell	2.9	1	10.7
	Number of unique LDA topics	1.7	1	2
	Indicator for a fault spell during phase maintenance	0	0	0.2
	Indicator for fault spell beginning on a Friday	0.2	0	0.4
	Indicator for fault spell beginning on a Monday	0.1	0	0.3
	Indicator for fault spell beginning on a Saturday	0	0	0.2
	Indicator for fault spell beginning on a Sunday	0	0	0.2
	Indicator for fault spell beginning on a Thursday	0.2	0	0.4
	Indicator for fault spell beginning on a Tuesday	0.2	0	0.4
Season	Indicator for fault spell beginning during December, January, or February	0.2	0	0.4
	Indicator for fault spell beginning during September, October, or November	0.3	0	0.4
	Indicator for fault spell beginning during June, July, or August	0.3	0	0.4

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4. Methodology

This chapter presents the methodology and theoretical framework used to estimate the causal effect of MilTech mechanics on the H-60 readiness outcomes of interest.

It is critical for the scientific validity of this analysis to identify a causal effect and not simply a correlation. To produce causal estimates of this effect, we first develop a model of causal dependencies structured as a directed acyclic graph (DAG). We then estimate the causal effects described by that model using an econometric (i.e., statistical) model to capture the functional and probabilistic nature of the data. Such a methodology can only estimate production function parameters in the local range of data available. Thus, the results of this analysis are valid for small movements in the status quo. In other words, this analysis provides reasonably valid predictions for small increases or decreases in the number of MilTechs for a given AASF. This analysis cannot be used to project outcomes following large changes in MilTech headcounts. We show an increase or decrease of one MilTech mechanic is valid for any AASF in fiscal year 2019.

A. Causal Model

There are many competing methodologies for producing causal models. This approach uses DAGs because they can be equivalent to the other approaches (such as potential outcomes) and are easily interpretable.[56] See Pearl 2009 for a survey of causal methodology in statistics.[57] In this analysis, each node in the DAG corresponds to a variable, while each directed edge indicates a causal relationship between those two variables.[58] Figure 17 shows a simplified version of the causal effects DAG for a given tail number, at a given AASF, for a given month. The nodes are parts, MilTechs mechanics, other aircraft, and fault spell duration. The edges show that parts affect fault spell duration (e.g., a shortage of parts can cause fault spell duration to increase) and MilTech

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[56] A more direct approach to estimating a production function follows from Ackerberg (2015). (Ackerberg, Caves and Frazer 2015). However, the approach requires having an intermediate price instrument (or something like it) for the number of MilTechs. The IDA team was unable to find such an instrument that was valid. Another approach is to use a system of structural equations common in the field of economics, but that approach is equivalent to the causal DAG in this situation.

[57] Judea Pearl, "Causal Inference in Statistics: An Overview," *Statistics Surveys*. 3. 96-146, 10.1214/09-SS057 (Institute of Mathematical Statistics, 2009).

[58] Note that the variable corresponding to a node can be unobserved. Unobserved means unobserved to the researcher (i.e., the researcher does not have data on the node). For example, work ethic of a MilTech is something that is observed by the supervisor and other MilTechs. However, there is no collected data on work ethic, thus it is unobserved.

mechanics affect fault spell duration (e.g., more MilTech mechanics can cause fault spell duration to decrease). The figure also shows that other aircraft affect both MilTech mechanics and fault spell duration. That is, an AASF that has a large number of other aircraft can cause the AASF to have a large number of MilTech mechanics, and the other aircraft can have an effect on the fault spell duration. See Appendix A for a discussion of causality and the full, expanded DAG.

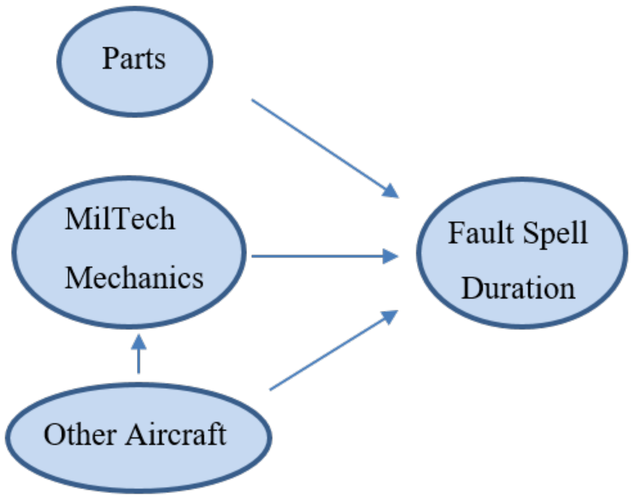

Figure 17. Simple DAG

The primary causal effect of interest for this analysis is represented by the edge from MilTechs to fault spell duration. Using methodology pioneered by Pearl and others, the DAG can be reduced to three groups of nodes. Those groups are then used in the econometric model for estimation. The three groups are treatment, adjustment, and outcome. The treatment node is MilTech mechanics, representing the number of line MilTech mechanics present at an AASF, which is the node whose value is treated (i.e., changed).[59] The treatment is increasing or decreasing the number of MilTech mechanics at an AASF. The outcome node is fault spell duration, which is the node of interest whose value responds to changes in the treatment node. The adjustment nodes contain nodes that either adjust for a confounding node (e.g., Other Aircraft) or reduce uncertainty (e.g., Parts). By adjusting for confounding, the confounding effect is removed from that correlation

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59 It is important to remind the reader that MilTech mechanics does not include backshop maintainers and the treatment node is only for the (direct) MilTech mechanics. This is because the IDA team was told during site visits that the effect of additional backshop maintainers would not show up in a direct manner using the 13-1 data fault data used to construct fault spell duration.

to arrive at the causal effect.[60] The specific causal effect estimated in this analysis is the *total* effect as opposed to the *direct* effect.[61,62]

B. Econometric Model

The econometric model parameterizes the causal model into a mathematical function relating observable variables (i.e., nodes) with unknown parameters (e.g., magnitude of causal effect) while capturing their probabilistic characteristics, such that the econometric model can be estimated with available data. The econometric model also produces estimates of uncertainty. Note that the estimates of uncertainty are of statistical uncertainty and not causal uncertainty. The causal model is assumed to be correct; its stability is scrutinized in the robustness checks. Statistical uncertainty is the uncertainty in the parameter estimates from the econometric model and is represented by 95% confidence intervals.[63]

The chosen econometric model consists of relating fault spell duration to the other variables using a semi-parametric log-linear generalized additive model (GAM). Here, the natural logarithm of fault spell duration is modeled as the sum of a non-parametric function of the number of MilTechs, a linear function of the other variables, and an unexplainable error assumed to be causally unrelated to the other variables.[64] Mathematically, the model is

$$\log\left(fault\ spell\ duration_{ij}\right) = f\left(Mechanics_{ij}\right) + X_{ij}'\beta + \epsilon_{ij}.$$

The indices i and j refer to tail number and fault spell number. The variable $\log\left(fault\ spell\ duration_{ij}\right)$ is the response variable, log spell duration for tail i and fault spell j. The $f\left(Mechanics_{ij}\right)$ is a non-parametric function that flexibly captures the non-linear effect of

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60 This strategy is also referred to as selection on observables. Joshua D. Angrist, Jörn-Steffen Pischke, *Mostly harmless econometrics: An empiricist's companion*. (Princeton University Press, 2008).

61 Judea Pearl, "Causal Inference in Statistics: An Overview," *Statistics Surveys,* 3. 96-146. 10.1214/09-SS057 (2009); E. Perkovic, J. Textor, M. Kalisch and M. H. Maathuis, "A Complete Generalized Adjustment Criterion," In *Proceedings of UAI 2015.*

62 The direct effect is the effect from hiring the additional mechanic while holding fixed the effect from intermediate outcomes such as the burden due to training a new mechanic. The total effect is the net effect of both having the additional mechanic and the effect from intermediate outcomes. The total effect is what would be observed upon increasing the number of MilTechs, as opposed to the direct effect, which would not be observed. For this reason, the econometric model does not control for tenure nor turnover because doing so would provide estimates of the direct effect, which would not be observed in reality.

63 The confidence interval is interpreted as "under repetition of this experiment the confidence interval procedure will capture the true casual effect 95% of the time" when repetition is performed over hypothetical ARNG worlds. The confidence interval should not be interpreted as containing the true casual effect 95% of the time.

64 S. Wood ,*Generalized Additive Models,* (New York: Chapman and Hall/CRC, 2017). https://doi.org/10.1201/9781315370279.

MilTechs on log fault spell duration.[65] The symbol X'_{ij} represents a vector (i.e., list) of covariates for tail i and fault spell j.[66] The symbol β represents a vector (i.e., list) of coefficients (i.e., weights) that represent the direction and magnitude of the relationship between the covariates and log fault spell duration. The variable ϵ_{ij} represents the exogenous discrepancy.

The outcome variable is the natural logarithm of fault spell duration. The natural logarithm transformation allows the model to be less affected by outliers and provides a simple interpretation of parameters. The function $f(Mechanics_{ij})$ captures the causal effect of interest. All other covariates (i.e., X'_{ij}) are adjustment covariates and are not necessarily causal. The difference function $d(Mechanics_{ij}) = f(Mechanics_{ij} + 1) - f(Mechanics_{ij})$ estimates the mean causal effect on log fault spell duration from having an additional mechanic in an AASF with a baseline number of MilTech mechanics, $Mechanics_{ij}$. The difference function is an approximation of a (forward) derivative, which (in log-linear models) is interpreted as the percent change in fault spell duration for a 1 unit increase in $Mechanics_{ij}$. Since fault spell duration is an accurate approximation of NMC time, changes in fault spell duration can be interpreted as changes in NMC time, which thus imply changes in MC time.

The covariates in X'_{ij} are adjustment variables that either control for confounding or increase precision. Note the coefficients β are called *nuisance* parameters with no analytical interest since they do not necessarily have a causal interpretation. The adjustment variables include other sources of personnel support, facility and customer unit effects, tail number specific effects, fault spell effects, and various fixed effects. The full list of adjustment variables can be seen in Table 6 in Appendix B.

Personnel support variables include the number of backshop maintainers, TempTechs, and ADOS. These variables control for the effects that other types of maintainers have on the maintenance process. Personnel support variables also include a series of upcoming personnel deployment indicators which control for changes in workloads and training commitments as a unit prepares for deployment.

The facility and customer unit variables consist of the average airframe age, utilization, and number and composition of aircraft. These variables control for the workload and type of work that the facility is performing. If a facility has a large workload, it may cause the length of new fault spells to have a long durations as the workload queue is processed.

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[65] The function is a cubic B-spline expansion. B-spline stands for basis spline and is a piecewise polynomial where the pieces meet at locations called *knots*. A cubic spline has a smooth second derivative, which is visually pleasing and flexible. Note the cubic B-spline basis is linear in parameters and thus the full model is still technically linear conditional on the knot locations. An initial model is first estimated with restricted maximum likelihood to obtain the knots prior to estimating the models on the multiply imputed data. The multiply imputed models are estimated with fixed knot locations. Standard errors are unconditional to the choice of knots.

[66] A covariate is an observable variable that *covaries* with the response variable (e.g., number of other aircraft covaries with fault spell duration).

Tail number variables include upcoming deployment indicators, age, utilization, and variant type. Fault spell specific variables include number of faults per spell, number of LDA topics, and a phase maintenance indicator. These variables are precision variables that reduce statistical noise in the estimates. Finally, fixed effects control for the facility, fiscal year, day the fault spell opened, model of helicopter (i.e., variant), calendar season, and dominate LDA topic.

C. Multiple imputation by chained equations (MICE)

As shown in section 3.D, some variables had missing observations. The econometric model requires observations to be non-missing. Common solutions are to either remove the variable or remove the missing observations for all variables. The first approach reduces causal validity and statistical power. The second approach reduces statistical power and requires a missing completely at random (MCAR) assumption, which is violated in this setting.[67] Alternatively, one can use multiple imputation using chained equations (MICE), which is a common technique used to impute missing data preserving statistical power and causal validity.[68]

The MICE algorithm uses covariates with observed or previously-imputed values to impute values for missing data. The procedure is iterative. For example, the (fully observed) fiscal year covariate (not shown in table) is used to impute customer deployment in one month or less, then fiscal year and customer deployment in one month or less are used to impute covariate customer deployment in three months or less. The procedure then iterates with the observed or imputed variables. The procedure is run in parallel with each chain as a different imputation. The last values of each imputation chain are used as the imputed values. We ran five parallel chains with forty iterations each. Convergence is assessed with standard visual inspection tools for assessing convergence of Markov Chain Monte Carlo (MCMC) methods. A separate model is estimated with each imputation. The results are then pooled with methods developed in Rubin 1987.[69]

The MICE algorithm requires a missing at random (MAR) assumption for validity. The MAR assumption is violated if the mechanism determining what values are missing correlated with the (unobserved) missing values. This is a plausible assumption in this case because the most frequent causes of missing values are due to misalignment of data collection periods and incomplete merges, both of which should be independent of the value of the unobserved missing data. The MICE algorithm can be inefficient if there is a large proportion of missing data, the effects of which will manifest with poor convergence of the MCMC chains.

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67 Missing completely at random means the mechanism determining what values are missing are not correlated with the observed or missing observations. Since most of the missing data is due to misaligned sampling frames, the fiscal year and facility fixed effects are correlated with the missing data mechanism.

68 S. van Buuren, *Flexible Imputation of Missing Data: Second Edition* (Boca Raton, FL: Chapman & Hall/CRC Press, 2018).

69 Donald B. Rubin, *Multiple Imputation for Nonresponse in Surveys* (Wiley, 1987).

The imputed models are estimated with a procedure equivalent to least squares. Least squares produce values for the coefficients that minimize the squared exogenous discrepancy of the estimated outcome value from the true outcome value.[70] The uncertainty in the parameter estimators is obtained by clustering at the tail number level, meaning the exogenous discrepancy for two arbitrary fault spells durations can be correlated within a given tail number.[71]

D. Estimating Changes in FMC and Flight Hours

We use separate models to infer impacts on FMC time and flight hours using estimated changes in MC time following the hypothetical addition of a single MilTech mechanic at each AASF. The FMC model estimates how much of the gain in MC time is comprised of FMC time, and the flight hours model attempts to capture the operational impact by estimating how many additional flight hours are produced from a gain in MC time. Both models require strong assumptions which may not hold. See the Caveats in section 5.A for a discussion.

The FMC model assumes that the MC time from an additional MilTech mechanic yields the same ratio of FMC to PMC as a helicopter with that same level of MC time without an additional MilTech mechanic. For example, according to the model, a helicopter with an additional MilTech mechanic and 6,000 MC hours in a fiscal year would have the same ratio of FMC-to-PMC time as a helicopter with 6,000 MC hours without an additional MilTech mechanic. This assumption would be violated, for instance, if an increase of one MilTech mechanic reduced NMC time but the time reduced was replaced with PMC time due to waiting on a PMC part to be delivered. The FMC model is a regression surface with fiscal year fixed effects estimated with annual helicopter-level readiness data. The model is

$$FMC\ time_{it} = f(MC\ time_{it}, Possible\ hours_{it}) + \ \delta_t + \epsilon_{it}.$$

The indices i and t refer to tail number and fiscal year, respectively. The variable $FMC\ time_{it}$ is the response variable, total annual FMC time for tail i in fiscal year t. The variable $Possible\ hours_{it}$ is the number of reportable readiness hours for a given helicopter and fiscal year. The $f(MC\ time_{it}, Possible\ hours_{it})$ is a non-parametric function that flexibly captures the non-linear effect of MC time and possible hours on FMC time.[72] The fiscal year fixed-effects, δ_t, absorb year-to-year idiosyncrasies and ensure the in-sample prediction errors are mean zero. The

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70 This linear model estimated with least squares has many nice statistical properties including, but not limited to, conditional expectation interpretation, unbiasedness, root-n consistency, and some robustness to model misspecification.

71 The clustering used is HC1. White, Halbert et al., "Some Heteroskedasticity-consistent Covariance Matrix Estimators with Improved Finite Sample Properties" *Elsevier Journal of Econometrics* 29, no 3 (Sept. 1985), 305. https://www.sciencedirect.com/science/article/pii/0304407685901587.

72 The non-parametric function for the FMC and flight hours models use a full tensor product cubic regression spline.

model is estimated as a GAM similar to the econometric model and has a sample size of 7,400 H-60 helicopter years.

The flight hours model has a similar assumption to the FMC model in that the MC time from an additional MilTech mechanic yields the same amount of flight hours as a helicopter with that same level of MC time without an additional mechanic. The flight hours model is a regression surface with fiscal year fixed effects estimated with annual helicopter-level readiness data combined with uniformed personnel data. The model is

$$Flight\ hours_{it} = f(MC\ time_{it}, Possible\ hours_{it}, Average\ pilots_{it}) + \delta_t + \epsilon_{it}.$$

The indices i and t refer to tail number and fiscal year, respectively. The variable $Flight\ hours_{it}$ is the response variable, total annual flight hours for tail i in fiscal year t. The variable $Possible\ hours_{it}$ is the number of reportable readiness hours for a given helicopter and fiscal year, and $Average\ pilots_{it}$ is the number of H-60 helicopter pilot months at the customer unit divided by the total number of H-60 helicopter months at the customer unit. The $f(MC\ time_{it}, Possible\ hours_{it}, Average\ pilots_{it})$ is a non-parametric function that flexibly captures the non-linear effect of MC time, possible hours, and the number of pilots available to fly the helicopter on flight hours. The fiscal year fixed-effects, δ_t, absorb year-to-year idiosyncrasies and ensures the in-sample prediction errors are mean zero. The model is estimated as a GAM similar to the econometric model and has a sample size of 7,260 H-60 helicopter years.

Total FMC time and flight hours with an additional MilTech mechanic in fiscal year 2019 is obtained using the total MC time from an increase in MilTech mechanics plugged into the estimated FMC and flight hours models. Then the difference between total FMC time with an additional MilTech mechanic and observed total FMC time is the impact on FMC time from a one MilTech mechanic increase. Likewise for flight hours. FMC time estimates are produced using 861 H-60 helicopter years in fiscal year 2019 among AASFs that had at least one H-60 helicopter year. Flight hour estimates are produced with 856 H-60 helicopter years among AASFs that had at least one H-60 helicopter year. There is a discrepancy between the number of helicopter years between the FMC and flight hours models due to missing data.

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5. Results

This chapter presents and interprets the results from the econometric analysis of how changes in MilTech mechanic headcounts at AASFs impact ARNG aviation readiness. We contextualize the results in terms of the addition of a single MilTech mechanic at a given AASF, but the findings equally apply to reductions and to changes of more than one individual so long as the change does not push the AASF outside the normal staffing bounds observed in this analysis. The first section presents results from the primary specification, and the second section discusses alternative specifications and robustness checks. We present the main result of the difference equation, facility level increases in MC time, helicopter level increases in MC time, fleet-wide increases in MC time, FMC time, and flight hours, and cost comparisons for alternative methods of increasing MC time. We also make recommendations on the basis of our findings.

A. Primary Specification

This section presents our estimates of the difference function described in section 4.B. Figure 18 presents these results in terms of the percent decrease in fault spell duration. The solid line shows the percent decrease in fault spell duration for a single typical fault spell given an additional MilTech mechanic (along vertical axis) across a range of different baseline MilTech mechanic staffing levels (along the horizontal axis), holding all else constant. Note that the inner 90% of AASFs are presented because the causal validity of the smallest and largest shops is suspect.[73]

[73] Causal validity requires comparing AASFs that are approximately equivalent in all aspects (except adjustment variables) but differ slightly in the number of MilTech mechanics. It is harder to make this comparison for AASFs that do not have a good pool of comparable AASFs. Thus, the x-axis is truncated at the 5% (6 MilTech mechanics) and 95% (36 MilTech mechanics) levels.

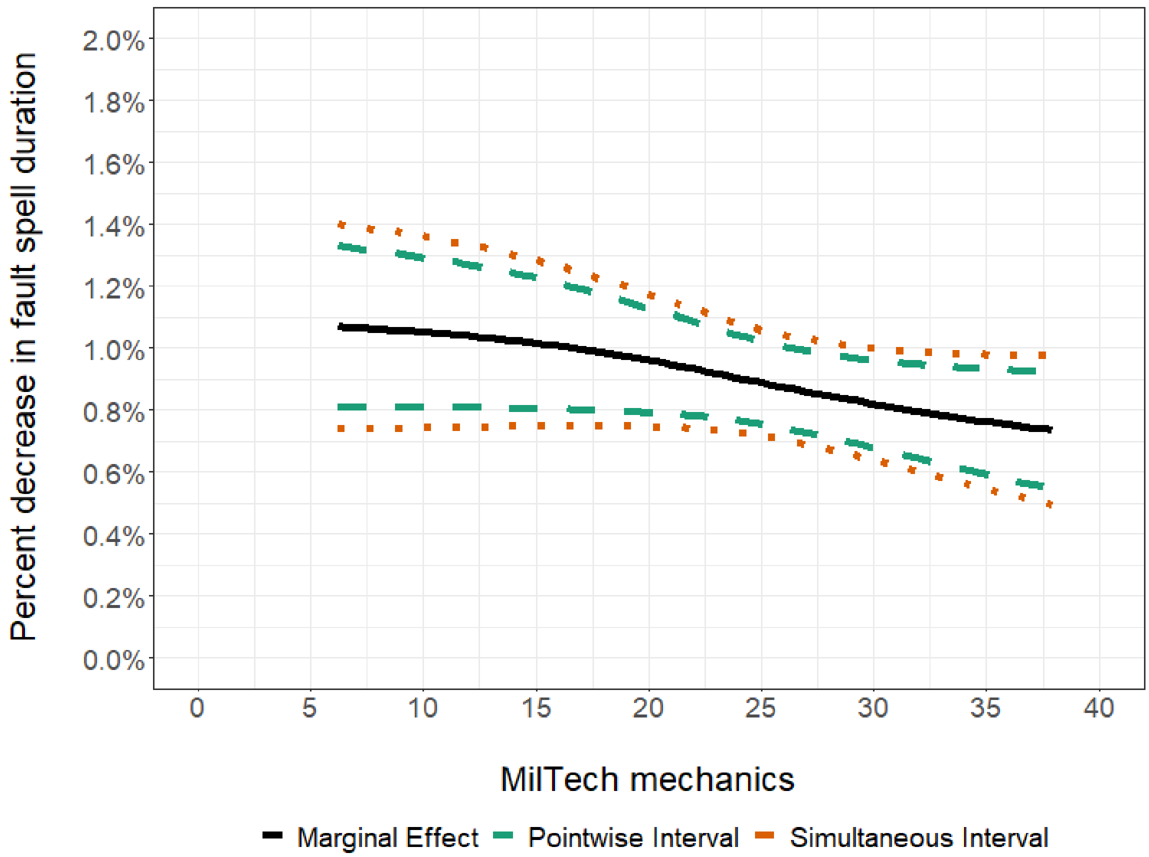


Figure 18. Marginal Effect: Main Model

Figure 18 shows that, holding all else constant, increasing the number of MilTech mechanics for smaller AASFs (in terms of the number of MilTech mechanics) causes a larger decrease in average fault spell duration. As the baseline MilTech headcount of the AASFs increases, the marginal effect of an additional MilTech diminishes.

As an example, the smallest AASF presented (which is the 5th percentile AASF in terms of size in fiscal year 2019) has 6 MilTech mechanics, and the estimated effect of having a 7th MilTech mechanic (a 16% increase) produces a decrease of fault spell duration by 1.1% on average, holding all else constant. The median AASF has 15 MilTech mechanics, and the estimated effect of having a 16th MilTech mechanic (a 7% increase) produces an average decrease of fault spell duration by 1.0%, holding all else constant. The largest AASF presented (which is the 95th percentile AASF) has 38 MilTech mechanics, and the estimated effect of having a 39th MilTech mechanic (a 3% increase) produces a decrease of fault spell duration by 0.7% on average, holding all else constant. Marginal returns to additional MilTechs are positive, and decreasing in magnitude as baseline manpower levels rise (i.e., decreasing returns to scale).

There are two intervals around the marginal effect line: a pointwise 95% interval represented by teal dashes and a simultaneous 95% interval represented by orange dots. The simultaneous interval is a confidence interval for the marginal effect curve in its entirety. This means that any arbitrary number of AASFs along the curve will *simultaneously* be contained within the simultaneous interval with 95% confidence. The most important implication of this is that the 95% simultaneous interval does not cross zero, meaning we can conclude that for all sizes of AASFs there is a negative marginal effect on fault spell duration by having an additional MilTech mechanic at the 0.05 level of significance, holding all else constant. Alternatively, the pointwise interval is a valid interval only at a given point (i.e., a specified number of mechanics at the AASF) on the marginal effect curve. For example, the 95% confidence interval for the average marginal effect of an additional MilTech mechanic at an AASF with 6 MilTech mechanics is from 0.8% to 1.3%, while an AASF with 15 MilTech mechanics is from 0.8% to 1.2%, and an AASF with 38 MilTech mechanics is from 0.6% to 0.9%, holding all else constant. However, those intervals would not be simultaneously accurate for an increase in MilTech mechanics in those three AASF sizes, in which case the simultaneous intervals would be more appropriate.

Facility and helicopter level increases in MC hours

To contextualize these results, one might consider the following:

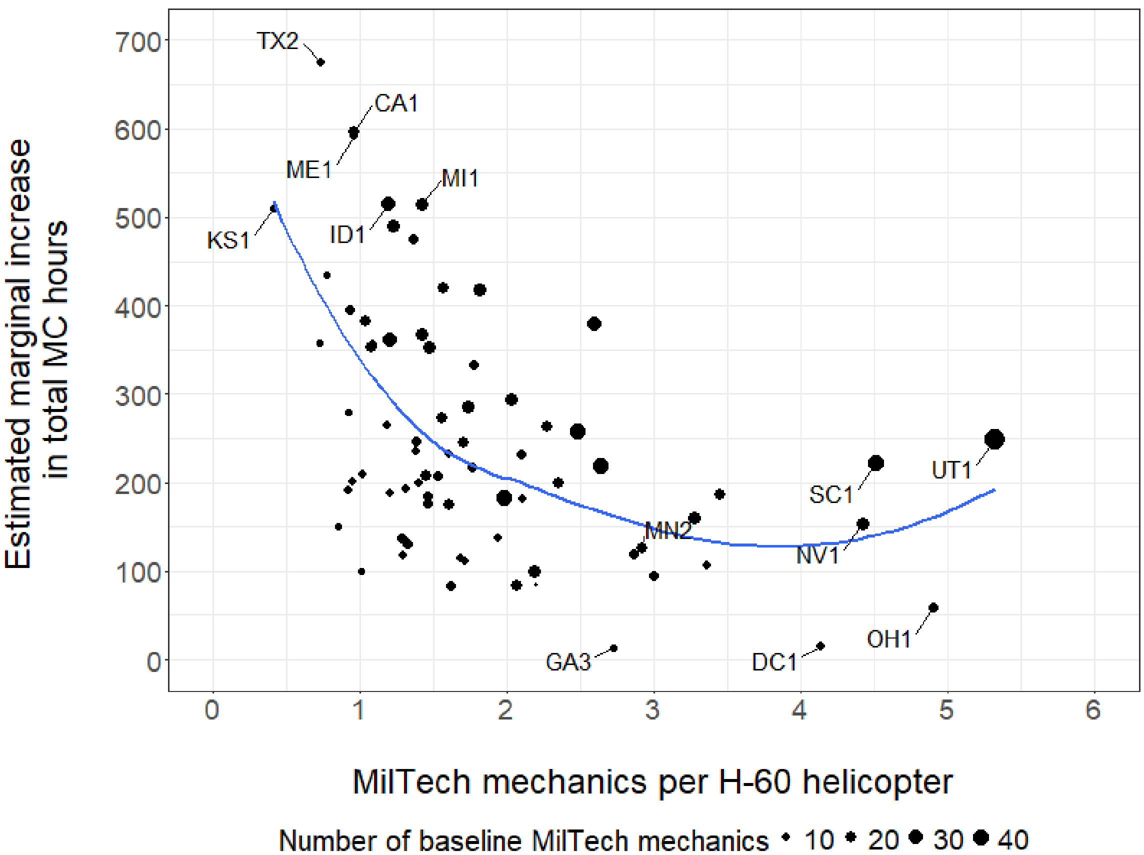
- What the average increase in total MC hours would have been in fiscal year 2019 for all H-60 helicopters had each AASF had an additional MilTech mechanic, and
- What the average increase in MC hours would have been in fiscal year 2019 for a single H-60 helicopter across AASFs of various sizes had each facility had an additional MilTech mechanic.

Figure 18 presents the first scenario, while Figure 20 presents the second. Both figures show a non-parametric locally estimated scatterplot smoothing (LOESS) line (in blue) which is a local average of the plotted points.[74] The smoothness of the line is chosen such that the line can show the local trend in a visually pleasing manner. In addition, Figure 19 shows the cumulative effect of the first scenario. There are no estimates of uncertainty provided due to project time and budget constraints.

Along the vertical axis, Figure 18 shows the counterfactual average increase in total MC hours for each AASF in fiscal year 2019 if each facility had an additional MilTech mechanic during the fiscal year. The horizontal axis shows the average number of MilTech mechanics per H-60 helicopter present in each AASF during fiscal year 2019. As an example, the TX2 AASF would have gained more than 650 additional MC hours on average in fiscal year 2019 if it had an additional MilTech mechanic. The points are sized proportional to the number of baseline MilTech mechanics that AASF in fiscal year 2019. As expected, AASFs with fewer MilTech mechanics

[74] W. S. Cleveland, E. Grosse, and W. M. Shyu, "Local regression models," Chapter 8 of *Statistical Models in S*, eds J.M. Chambers and T.J. Hastie (Wadsworth & Brooks/Cole, 1992).

per H-60 helicopter tend to have larger increases in the average total MC hours at the AASF.[75] Facilities with low levels of baseline MilTech mechanics, a relatively small number of baseline mechanics per H-60 helicopter, and large number of H-60 helicopters will experience the largest productivity gain when given an additional MilTech maintainer. This effect is slightly obscured in the graphic because the MilTech mechanic count includes mechanics who work on helicopters other than the H-60 helicopter, and the impact on MC time only measures the effect for H-60 helicopters. For example, TX2 only had UH-60 Black Hawks in fiscal year 2019, while GA3 had HH-60 Pave Hawks and CH-47 Chinooks, this explains their relative positions.



Notes: Dot size is proportional to the number of total baseline MilTech mechanics, which include mechanics for H-60 helicopters, CH-47 Chinooks, and AH-64 Apaches. By contrast, the horizontal axis displays the ratio of total baseline MilTech mechanics per H-60 helicopter.

Figure 19. Marginal Effect of Additional MilTech Mechanics at ARNG AASFs on H-60 MC Hours

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75 This is due to more helicopters causing more total fault spells and longer aggregate fault spell duration. Thus, the reduction in aggregate duration is larger. Only H-60 helicopters are counted.

Many of these facilities also contain other helicopters and the MilTech mechanics (identified from position description 8852) can work on them as well.

The AASF MN2 experienced a helicopter crash during a maintenance test flight in December 2019, resulting in the deaths of three ARNG members. The facility was not an outlier in the number of MilTech mechanics relative to the number of H-60 helicopters (although the facility also had CH-47 Chinooks). This suggests they may not have been strained in the number of MilTech mechanics prior to the crash.

The blue line represents the local average increase in total MC hours that would be experienced by AASFs with a similar number of baseline MilTech mechanics per H-60 helicopter if their MilTech manpower increased by one individual. The downward sloping regions of the figure's fitted blue line indicates that for the average facility in that range, as baseline MilTech manpower per H-60 helicopter increases, the marginal increase in total MC hours decreases. The right tail of the blue line is pulled up by the UT1 AASF, which has exceptionally large number of MilTech mechanics per helicopter.[76] If UT1 is removed, the right tail becomes mostly flat.

One way that ARNG might measure the impact of acting on these results is to consider a hypothetical exercise in which additional MilTechs are assigned to AASFs in order of greatest to least marginal productivity. In this exercise, the first additional MilTech mechanic is assigned to the AASF that would experience the largest gain in MC hours; the second additional MilTech is added to the AASF with the second-largest marginal MC hours productivity gain; and so on. We term the total overall gain in MC hours resulting from gradually adding MilTechs in this manner the "Hypothetical Cumulative Increase in MC Hours." Figure 19 plots this measure for facilities as they existed in fiscal year 2019, and shows how the measure changes as more facilities are given a hypothetical additional MilTech mechanic, in order from most productive to least productive. Returns to each additional MilTech are positive and display decreasing marginal returns until the highest levels of staffing increases are considered (that is, eventually there is no additional MC hour gained from an additional MilTech).

[76] The UT1 AASF in this case is called an outlier. We inspected this data point, and while UT1 does have an exceptionally large number of MilTech mechanics per H-60 helicopter, we could not conclusively determine that this is due to erroneous data. Therefore, we included UT1 in the analysis.

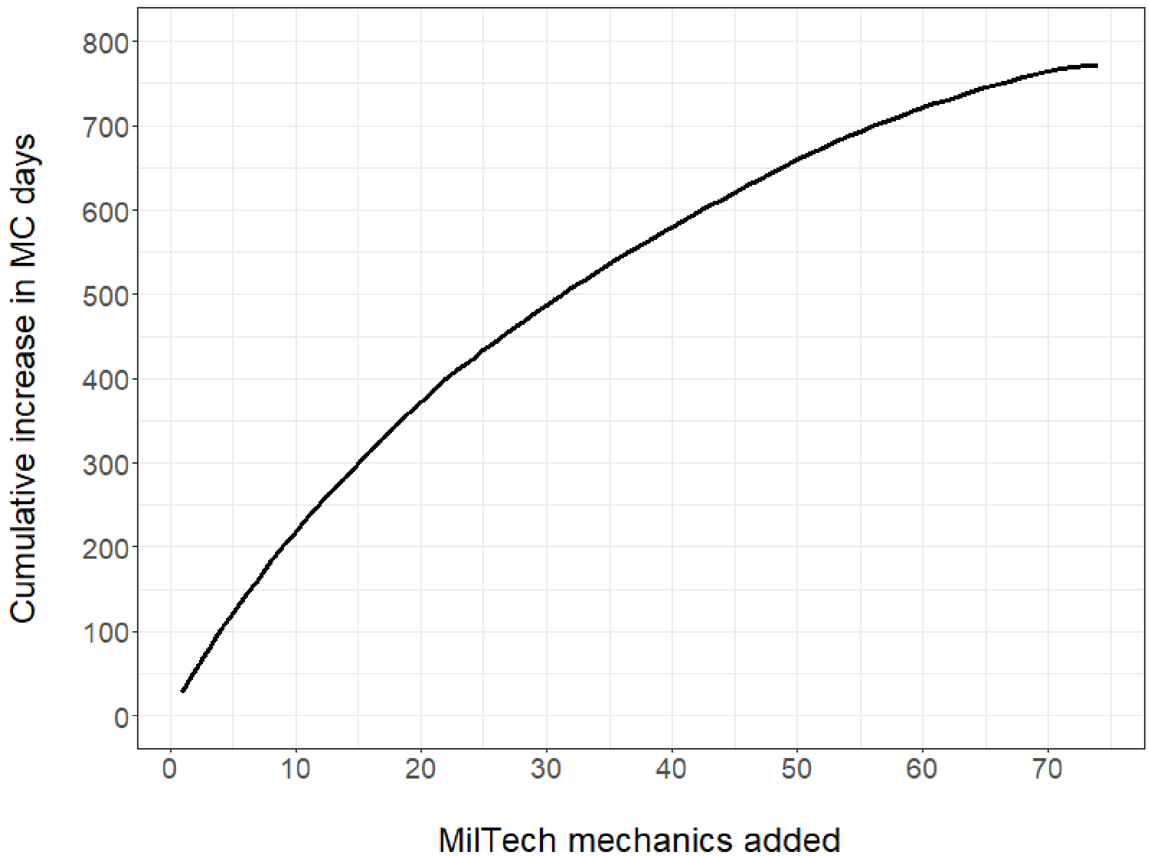

Figure 20. Hypothetical Cumulative Increase in MC Days

Figure 20 presents the counterfactual average number of additional MC hours for a single H-60 helicopter in fiscal year 2019 at various AASF of various levels of MilTech mechanics per H-60 helicopter, if each facility had an additional MilTech mechanic. Each point represents the number of additional MC hours from an additional MilTech mechanic if the helicopter was located all year at an AASF of the corresponding baseline size. There is one point per AASF. It can be seen that an individual H-60 helicopter will gain 23 to 30 additional MC hours if its AASF had an additional MilTech mechanic in fiscal year 2019. The blue line shows that an H-60 helicopter in 2019 would have had approximately 26 additional MC hours on average if a facility with 1 MilTech mechanic per H-60 helicopter had an additional MilTech mechanic. It also shows that the change in MC hours decreases and then flattens as the number of MilTech mechanics per H-60 helicopter increases.

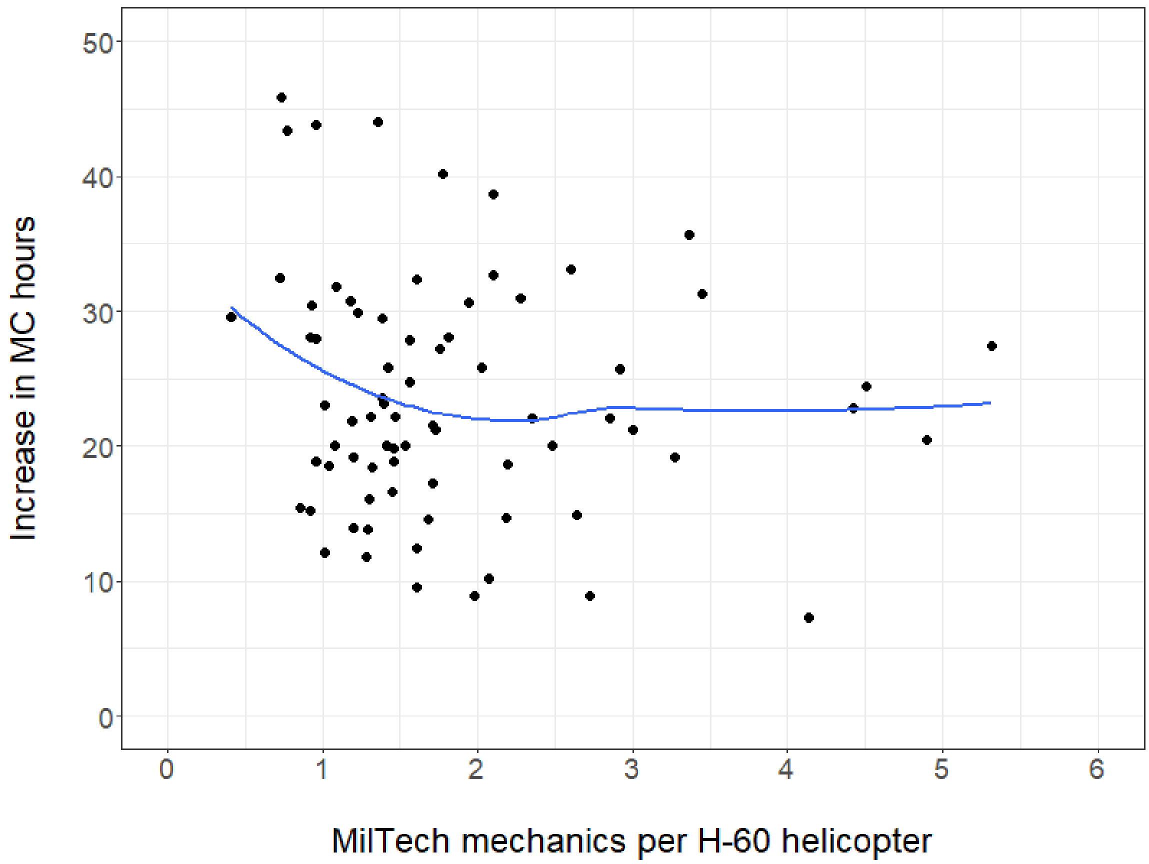

Figure 21. Marginal Effect of Additional MilTech Manpower for a Single H-60 Helicopter

Fleet-wide impacts and cost comparison

If every AASF with at least one H-60 helicopter year in fiscal year 2019 had an additional MilTech mechanic (74 additional MilTechs and 861 H-60 helicopter years total, then there would have been an increase of 18,509 additional MC hours (771 days, or 0.96% decrease in NMC time fleet wide in expectation for H-60 helicopters. Of the gained MC time, 17,449 hours (727 days were an increase in FMC time and the remaining 1,056 hours (44 days were an increase in PMC time. Thus, 94% of the gained MC time is FMC time. Likewise, the gained MC time produced 353 additional flight hours.

The median base annual salary of a MilTech mechanic in fiscal year 2019 was $65,478, and thus, annual cost for 74 MilTech mechanics is roughly $4.8 million. Therefore, an additional MC hour costs approximately $262 in annual wages. Alternatively, the ARNG can obtain an additional MC hour by borrowing a UH-60M Black Hawk at a much more expensive price of $2,920 from a different DOD component.[77]

[77] Office of the Under Secretary Of Defense, "Fiscal Year (FY) 2020 Department of Defense (DOD) Fixed Wing and Helicopter Reimbursement Rates," (Washington, DC: DOD, Oct. 2019), 1-8. www.comptrollerdefense.gov/Financial-Management/Reports/rates2020/.

Instead of borrowing an additional helicopter, the ARNG could hypothetically purchase new helicopters. A typical H-60 helicopter had 5,723 MC hours in fiscal year 2019. As a result, hiring an additional MilTech mechanic in 74 facilities is roughly equivalent to gaining 3.2 additional H-60 helicopters. The gross weapon system unit cost of a new UH-60M Black Hawk is approximately $23 million dollars; thus, 3.2 additional UH-60M Black Hawks would cost approximately $74 million.[78] Further, the annual operating and support costs of a UH-60M Black hawk is $1.4 million per helicopter-year; thus, the total annual cost for operating and support would be $4.5 million per year.[79] Additional MilTech mechanics are thus a cost-effective means available to the ARNG to expand MC hours of the fleet.[80]

Comments on interpretation

The estimates of MilTech mechanic marginal productivity provided in these analyses are likely underestimates, for several reasons. First, any additional MilTech labor would be applied to a larger pool of maintenance work than is considered in this analysis (such as depot work at AASFs and PMC time becoming FMC time).[81] Second, since the MilTech mechanic headcount is obtained by summing the number of MilTechs with the 8852 position description, all these results could be further underestimated. The 8852 position description includes not just H-60 helicopter mechanics but other aircraft mechanics as well (such as those servicing the CH-47 Chinook). Thus, AASFs that have both H-60 helicopters and CH-47 Chinooks, for example, could downward bias the estimates, although variables for other aircraft were included in the econometric model to help mitigate this bias.

In addition, readers should note that productivity estimates for changes in MilTech manpower levels are only valid for small changes in staffing levels around the levels studied here. In other words, these results provide reasonably valid, actionable predictions for small increases or decreases in MilTech mechanic headcounts for a given AASF. An acceptable local range can be seen in Figure 18 by inspecting how much variation in MilTech staffing each AASF year experiences (with deployments removed). The dots represent the standard deviation of MilTech mechanic staffing on the y-axis against the mean MilTech mechanic staffing at the AASF by fiscal

[78] Exhibit P-5, PB 2021 Army, Line Item A05002 / UH-60 Black Hawk (MYP).

[79] Program Office Estimate, UH-60M Black Hawk Helicopter, Selected Acquisition Report ,December 2018. Adjusted for inflation.

[80] This is a simplified comparison. MilTechs cost more than their salary due to benefits, training, etc.

[81] The estimates in hours are calculated by applying the percent decrease in fault spell duration to reported NMC time in the readiness data. The estimate is an underestimate because maintenance for depot faults at the AASFs or faults for aircraft not reported in the readiness data are not included. Additionally, faults for deployed aircraft are not included. PMC faults are not included, they would presumably shorter as well, leading to an increase in more FMC time. Additionally AASFs that have aircraft other than UH-60 Black Hawks would presumably benefit as well.

year level. The green dots are for fiscal year 2011 through 2018 and the orange dots are for fiscal year 2019.

A rule-of-thumb is that the change in MilTech mechanic staffing can be plus or minus one standard deviation from the current staffing. For example, by looking at the black line of best fit, AASFs with five MilTech mechanics at baseline have an average standard deviation a little larger than one. Thus, the model will produce reasonable estimates for plus or minus one MilTech mechanic for an AASF with five MilTech mechanics at baseline. An AASF with 25 MilTech mechanics has an average standard deviation of 2.5. For an AASF with 25 MilTech mechanics at baseline, the model will therefore produce reasonable estimates for plus or minus two MilTech mechanics from baseline. The orange dots show that no fiscal year 2019 AASF has less than five MilTech mechanics at baseline, and no fiscal year AASF is outside the normal MilTech mechanic staffing bounds. Therefore, we can conservatively conclude that the model will produce reasonably valid MC hour predictions for an increase of one MilTech mechanic at any fiscal year 2019 AASF.

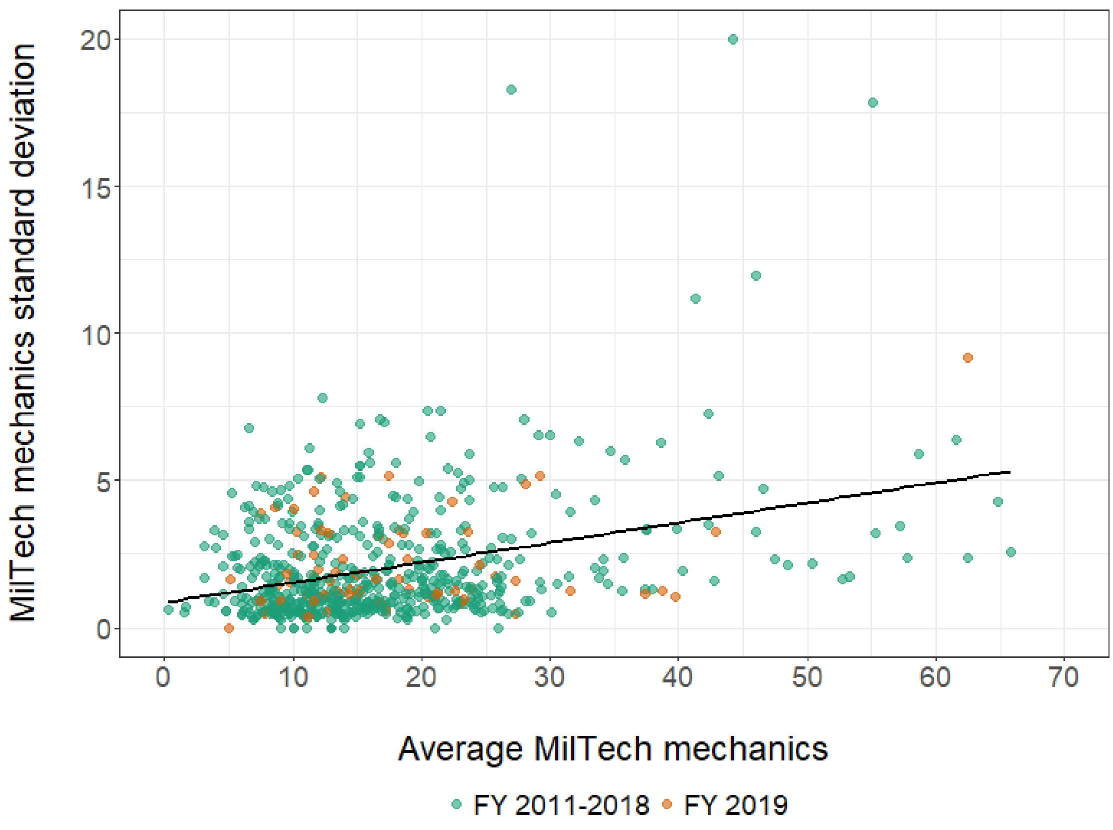

Figure 22. AASF MilTech Variation

The FMC and flight hours models produce simple rough approximations to what the likely fleet-wide impact of an increase in MC time could be on FMC and flight hours. A strong causal interpretation should be avoided. The models' validity critically depend on the impacts on FMC and flight hours from the MC time with an additional MilTech mechanic are equal on average as a helicopter with that same level of MC time without an additional mechanic. This assumption is not tested and likely not valid. A worrying sign is that the FMC model estimates 65% of fiscal year 2019 H-60 helicopters would experience a decrease in FMC time with an additional MilTech mechanic. Likewise, the flight hours model estimates 48% of fiscal year 2019 H-60 helicopters would have a decrease in flight hours with an additional MilTech mechanic.[82] While the individual estimates are poor, we hope in aggregate the fleet-wide estimates are reasonably accurate. A more advanced model would directly model the impacts of an additional MilTech mechanic on FMC and flight hours directly under a causal structure and without the MC time intermediary. However, such a model could not be pursued due to time and budget constraints. Since the flight hours model had five fewer helicopter years than the estimates for readiness metrics, the estimated increase in flight hours is an underestimate. Results for the parametric linear terms of the GAM in the econometric model are presented in Appendix B. However, those estimates are for nuisance parameters, and cannot be interpreted as causally related to fault spell length.

B. Alternative Specifications and Robustness Checks

The econometric analysis in this analysis utilized a null hypothesis significance test (NHST) where the econometric model is restricted to assume the null hypothesis that there is no relationship between the number of MilTech mechanics and the outcome of interest. The data then provides information to the model about whether that restriction is reasonable. If the data shows strong evidence of a relationship between the number of MilTech mechanics and the log fault spell duration, then the researcher can reject the null hypothesis and conclude there is indeed a relationship between the number of MilTech mechanics and log fault spell duration. In this case, since the simultaneous confidence bands do not cross zero in Figure 18, we can conclude that increasing MilTech mechanics at an AASF does, in fact, have a negative effect on fault spell duration for AASFs of any size.

NHST has a problem that rejecting (or not rejecting) the null hypothesis can only correspond to the scientific question of interest provided that all preceding assumptions and modeling decisions are valid. This is known as Duhem's problem.[83] For example, throughout this analysis many decisions were made (e.g., assuming fault start times occur before fault end times, dropping helicopters that do not appear to be at an AASF, specification of the DAG model, assuming linearity of adjustment variables). Some assumptions seem innocuous, such as assuming fault start times occur before fault end times. Some assumptions seem reasonable but are hard (if not

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[82] An additional MilTech mechanic causing an increase in MC time could lead to less FMC time by allowing a helicopter to fly more and incur increased maintenance demands through increased PMC time. However, we could not think of a reason why an increase in MC time could lead to less flight hours. Since the aggregate effect is positive, the individual negative effects are of a small magnitude. The flight hours are unexpectedly low because a helicopter that is rarely used tends to have low flight hours and a large amount of MC time. Our simple models do not account for this selection bias.

[83] Deborah Mayo, *Statistical Inference as Severe Testing: How to Get Beyond the Statistics Wars* (Cambridge: Cambridge University Press, 2018).

impossible) to check, such as the causal model or dropping helicopters that do not appear to be at an AASF (How can one be certain all such helicopters have been dropped and no unnecessary ones have been dropped?). Some assumptions can be replaced with other reasonable (and potentially valid) assumptions such as which set of adjustment variables to use. Ideally, each assumption would have a testable implication with which to verify its validity in isolation. For example, one could check that helicopters not at the AASF are dropped by inspecting the flight logs for every single helicopter, but this is infeasible for this analysis.

Robustness checking scrutinizes Duhem's problem in the context of a given analysis. Robustness checking typically consists of two procedures: checking testable implications and replacing some assumptions with other reasonable assumptions and seeing if the same results hold.

Robustness checks are performed by first restricting the non-parametric function for MilTech mechanics to be linear $f\left(Mechanics_{ij}\right) = \gamma Mechanics_{ij}$ to see if similar results are obtained on average by pooling facilities of all sizes. Second, γ is re-estimated with different sets of adjustment variables to explore the sensitivity of γ. If the DAG is correctly specified, then there should not be much change in γ for different adjustment sets.

We briefly pursued direct analysis of reported NMC rates as an outcome measure (instead of fault spell duration). The results suggested estimates of similar magnitudes but increased statistical noise made the results inaccurate. The increased statistical noise was presumably due to the loss of information from not knowing the continuity of fault spells between reporting periods. We also estimated the main specification with and without the LDA topic covariates. Inclusion of them reduced standard errors but did not affect point estimates to a meaningful degree. The results are not presented due to a lack of time and resources.

1. Linearity

The coefficient of the restricted model is estimated to be -0.009, which is interpreted as an additional MilTech mechanic causes a 0.9% decrease in average fault spell duration, holding all else constant. The coefficient has a p-value of .003 and is thus significant at the 0.05 level of significance. The 95% confidence interval is from -0.014 to -0.003, corresponding to a decrease in fault spell duration between 0.3% and 1.4%. The full table of estimates is presented in Appendix B. This result should not be surprising considering that when a linear model approximates a non-linear function, the resulting coefficient estimate is a weighted average of the derivative of the function over the covariate space.[84] While this restricted linear model does not capture the richness of the marginal effects of the GAM, it does provide a single point estimate approximation that can be useful for communicating the results of this analysis with a single number.

[84] Andreas Buja et al., "Models as Approximations I: Consequences Illustrated with Linear Regression," *Statistical Science* 34, no. 4 (2019): 523–544. https://projecteuclid.org/euclid.ss/1578474016.

2. Alternative Adjustment Sets

If the DAG is properly specified, there are alternative sets of adjustment variables that should produce equivalent estimates of the causal effect. Five alternative adjustment sets were obtained using methodology developed in Perkovic et. al. (2019).[85] Using these five alternative models, the pointwise estimates of the coefficient of the restricted model ranged from -0.010 to -0.006. These point estimates fall inside the 95% confidence interval of the model assuming full linearity.[86]

C. MilTech Mechanic Investment Recommendations

Given these results, how might ARNG allocate investments in MilTech manpower to produce additional aircraft readiness? The ARNG could decide to invest equally in MilTech mechanics in all states and territories, or they could implement targeted investments. Investing in MilTech mechanics equally across the ARNG would have resulted in an estimated 0.9% reduction in NMC, for an increase of 771 additional MC days fleet-wide for the H-60 helicopters in fiscal year 2019, holding all else equal. However, increasing MilTech mechanic headcounts at facilities with an already large number of MilTech mechanics per H-60 helicopter will have lower payoff than more targeted investments.

Instead, the ARNG could target MilTech investments for a desired outcome. For example, Figure 18 shows that the facilities with fewer MilTech mechanics per H-60 helicopter will experience the greatest increase in total MC time for an additional MilTech in fiscal year 2019, holding all else equal. In addition, facilities near the top of the figure should experience the greatest increase in total MC hours among their H-60 helicopter fleets. If the goal were to increase the MC time for individual H-60 helicopters, then investments should be made in facilities with fewer MilTech mechanics per H-60 helicopter, as can be seen from Figure 20.

Since helicopter systems besides the H-60 helicopter would presumably benefit from additional MilTech mechanics as well, the ARNG could focus investments at facilities with a small number of MilTech mechanics per helicopter (not just H-60 helicopter). We anticipate that our results would generalize fleet-wide, however we do not have quantitative evidence to support such a claim.

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85 Johannes Textor and Benito van der Zander, dagitty: Graphical Analysis of Structural Causal Models. R package version 0.2-2 (2016). https://CRAN.R-project.org/package=dagitty; E. Perkovic, J. Textor, M. Kalisch and M. H. Maathuis, "A Complete Generalized Adjustment Criterion," In *Proceedings of UAI 2015.*

86 While this is not sufficient to statistically conclude there is no difference between the alternative specifications and the main specification, it is strong evidence.

6. Conclusions

This analysis is part of a broad effort by the ARNG to quantify the value of various types of ARNG manpower investments in producing readiness outcomes. We investigated the relationship between FTS and aviation readiness, particularly H-60 helicopter NMC time. Using causal econometric methods, we found that increasing the number of MilTech mechanics at ARNG AASFs reduces the time that H-60 helicopters spend in a maintenance status, to a statistically significant extent, for AASFs of all sizes. We estimate that overall, an additional MilTech mechanic decreases average fault spell duration by 0.7% to 1.1% depending on the size of the AASF (in terms of baseline MilTech mechanics), holding all else constant. At existing AASFs, a single MilTech mechanic added to each ARNG AASF with at least one H-60 helicopter year would produce an increase of approximately 23 to 30 additional MC hours per H-60 helicopter, or 3.2 additional ready helicopter years when accumulated across the ARNG H-60 helicopter fleet. We found this to be a cost-sensitive approach to increasing the MC time for the H-60 helicopter fleet when compared to borrowing or buying UH-60M Black Hawks. These results can provide targeted staffing recommendations appropriate for a resource-constrained environment by identifying where additional MilTech mechanics would most improve H-60 readiness.

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Appendix A.
Causality and Expanded DAG

One way to define causality is with potential outcomes.[1] Define $Y(x)$ to be the *outcome* Y under the state x. The state x is also called a *policy* variable (it is sometimes also called a *treatment* variable). For example, let Y be the fault spell duration for a given tail number in a given month and x be the number of MilTech mechanics at the residential AASF in that month. Suppose the AASF has 10 MilTechs mechanics and the helicopter has a fault spell duration of 26 hours; then $Y(x) = Y(10) = 26$ hours. If instead the AASF has 11 MilTechs mechanics and the fault spell duration is 24 hours then $Y(x) = Y(11) = 24$ hours. The causal effect of hiring an additional MilTech mechanic is $Y(x+1) - Y(x)$. In our example, the causal effect is $Y(11) - Y(10) = 24 - 26 = -2$ hours. That is, an additional MilTech mechanic *causes* a 2-hour reduction in fault spell duration.

However, only one state of the world is observed at any given time. You cannot simultaneously observe the same AASF with 10 and 11 MilTechs mechanics. This is the fundamental problem of causal statistics. The unobserved state and outcome are called counterfactuals because they are *counter* to the *factual* world that is observed.[2] For example, if an additional MilTech mechanic is not hired, then the observed world is $Y(10) = 26$ hours, and a counterfactual world is $Y(11) = 24$ hours. The field of causal statistics establishes rules and procedures that allow the researcher to find observed worlds that are used in place of unobserved counterfactual worlds in order to provide causal estimates (provided the rules be satisfied). These procedures have been mathematically proven to be valid.

Figure A-1 presents the expanded DAG showing all relevant causal relationships. The nodes contain variables and the solid arrows represent causal direction. Some variables have subscripts "t", "-t", and "t-1." The "t" subscript represents the current time period, "-t" represents all previous time periods, and "t-1" represents the previous time period. Variables without a subscript are assumed to exert influence in the current time period. The subscript was omitted to avoid clutter.

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1 For a survey of causality in the social sciences, see Brady, Henry E., "Causation and explanation in social science," T*he Oxford Handbook of Political Methodology* (Oxford University Press, 2008).

2 Colloquially, observed states of the world are sometimes also referred to as counterfactuals.

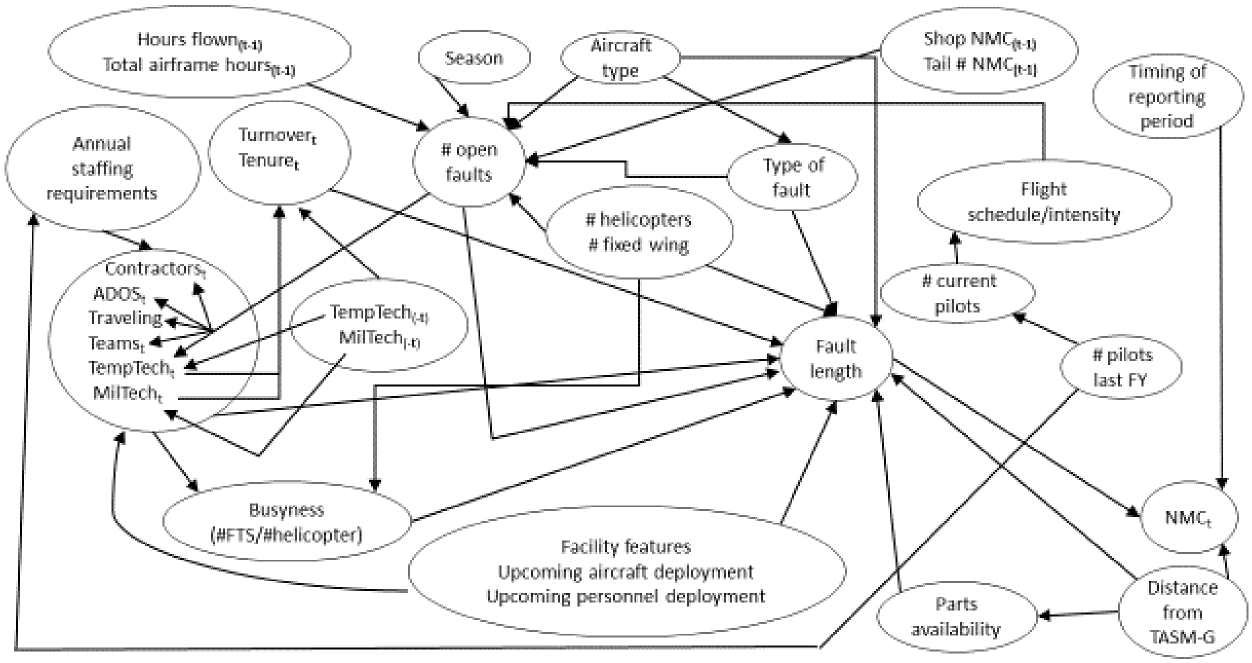

Figure A-1. Expanded DAG

The main relationship of interest is from the MilTech *policy*, representing MilTech mechanics, to fault length to the *outcome* NMC_t, representing fault spell duration. This is performed by defining fault length such that it is a measure of NMC, effectively collapsing Fault length and NMC_t. A *policy* is a variable that one wishes to change. An *outcome* variable is the variable that one wishes to influence. There are two causal pathways from MilTech to fault length: the first is directly from the node containing all FTS, the second is through the node containing tenure, turnover, and busyness. Tenure, turnover, and busyness are considered causal *mediators* because they mediate the effect of MilTechs on fault length (mediators are also called *intermediate outcomes*). If there is an increase in the number of MilTechs, then there is a decrease in tenure assuming the MilTech is hired with little experience relative to the other MilTechs currently employed. There are similar stories for turnover and busyness.

There are two other main types of variables in this analysis: *confounder* variables and *precision* variables. Confounders are uncontrollable variables that have causal effects on the outcomes of interest and cause the policy variable. The number of open faults is an example of a confounder for NMC time; if there are many open faults then the AASF might increase FTS to handle the large workload. If confounders are not controlled for, then the causal estimate will not isolate the effect of MilTech on fault length. There are many other confounders in this DAG such as upcoming deployments, facility features, and all variables that causally influence other confounders.

The presence of confounding nodes is one of the reasons behind the phrase "correlation is not causation." In Figure A-1, number of helicopter represents a confounding variable (through number of open faults). It is confounding because if there is a large number of aircraft at the AASF, there will likely be additional MilTech mechanics and there *could* be more fault length (if there are not enough additional MilTech mechanics to fully support the additional aircraft). It would follow that a raw correlation between the number of MilTechs mechanics and fault length would show a positive relationship between MilTech mechanics and fault length (e.g., more MilTech mechanics is associated with more fault length). By adjusting for confounding, the confounding effect is removed from that correlation to arrive at the causal effect.[3]

A *precision* variable causally influences fault length, but has no effect on MilTech staffing. For example, parts availability affects fault length, but not MilTechs. If parts are available, then fault length decreases, but there is no immediate effect on the staff.[4] Including precision variables reduces statistical uncertainty, but does not impact bias of the estimators. The specific causal effect estimated in this analysis is the *total* effect as opposed to the *direct* effect.[5] To understand the difference, consider the example of hiring a new MilTech mechanic. There are two competing effects from hiring a new MilTech mechanic. The first (and most obvious) effect is there is an additional mechanic available to assist with maintenance. This effect can help reduce fault spell duration. However, the new MilTech mechanic is likely inexperienced and will need training, which can reduce the productivity of the other mechanics who assist with the training. The direct effect is the effect from hiring the additional mechanic while holding fixed the effect from training. The total effect is the net effect of both having the additional mechanic and the effect from training (including both direct and indirect effects). The total effect is what would be observed upon increasing the number of MilTechs, as opposed to the direct effect, which would not be observed. For this reason, the econometric model does not control for tenure, turnover, nor busyness because doing so would provide estimates of the direct effect, which would not be observed in reality.

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3 This strategy is also referred to as selection on observables. Angrist and Pischke, *Mostly harmless econometrics: An empiricist's companion* (Princeton University Press, 2008).

4 It is important to take note of the temporal nature of causality. A current parts availability does not impact current FTS. However, it could impact future FTS staffing.

5 Judea Pearl, "Causal Inference in Statistics: An Overview," *Statistics Surveys*. 3. 96-146. 10.1214/09-SS057 (2009); E. Perkovic, J. Textor, M. Kalisch and M. H. Maathuis, "A Complete Generalized Adjustment Criterion," In *Proceedings of UAI 2015.*

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Appendix B.
Regression Model

The table of parametric estimates from main specification is shown in Table B-1. The number and name of the parameter is in the first two columns, followed by the parameter estimate, then the standard error, then the p-value, and lastly the individual significance level. The individual significance level has * for p-value less than 0.1, ** for p-value less than 0.05, and *** for p-value less than 0.01. The numbers have been rounded to make the table fit on the page. There are no causal estimates. All the estimates are for nuisance parameters and have little scientific interest.

The table of estimates from Section 5.B.1 are shown in Table B-2. The number and name of the parameter is in the first two columns, followed by the parameter estimate, then the standard error, then the p-value, and lastly the individual significance level. The individual significance level has * for p-value less than 0.1, ** for p-value less than 0.05, and *** for p-value less than 0.01. The numbers have been rounded to make the table fit on the page. The only causal estimate is in bold. All the other estimates are for nuisance parameters and have little scientific interest.

Both tables exclude covariates for AASF fixed effects and for LDA modal dominant topic indicators.

Table B-1. Selected Parametric Estimates from Main Specification

Adjustment variable	Coefficient	Standard Error	p-value	
(Intercept)	4.46	0.088	0	***
MilTech backshop maintainers	0.013	0.001	0	***
TempTech mechanics	0.004	0.001	0	***
TempTech backshop maintainers	0.011	0.002	0	***
ADOS mechanics	-0.009	0.001	0	***
ADOS backshop maintainers	0.032	0.003	0	***
Man hours worked by traveling teams at the AASF	0	0	0.849	
MilTech mechanics mobilized, deployed, or on leave	-0.006	0.001	0	***
MilTech backshop maintainers mobilized, deployed, or on leave	0.009	0.001	0	***
Fraction of AASF maintainers mobilized or deployed in current month	-0.141	0.038	0	***
Fraction of AASF maintainers mobilized or deployed in 1 month	-0.305	0.049	0	***
Fraction of AASF maintainers mobilized or deployed in 3 months	0.228	0.067	0.001	***
Fraction of AASF maintainers mobilized or deployed in 6 months	-0.035	0.088	0.692	
Fraction of AASF maintainers mobilized or deployed in 12 months	0.028	0.05	0.572	
Mean NMC% of AASF's H-60 helicopters in the prior month	-0.023	0.014	0.092	*
Mean NMC% of AASF's H-60 helicopters in the prior 3 months	0.274	0.017	0	***
Mean NMC% of AASF's AH-64, CH-47, and OH-58 helicopters in the prior month	-0.069	0.013	0	***
Mean NMC% of AASF's AH-64, CH-47, and OH-58 helicopters in the prior 3 months	0.195	0.022	0	***
Mean hours flown of AASF's helicopters in the prior month, excluding UH-72 Lakotas	0.001	0.001	0.098	*
Mean hours flown of AASF's helicopters in the prior 3 months, excluding UH-72 Lakotas	0	0	0.876	
Mean airframe hours of AASF's helicopters in the prior month, excluding UH-72 Lakotas	0	0	0.945	
Number of H-60 helicopters at the AASF	0.004	0.001	0	***
Number of AH-64, CH-47, and OH-58 helicopters at the AASF	-0.004	0.001	0	***
Number of UH-72 Lakotas at the AASF	0.008	0.002	0	***
Indicator for any fixed wing aircraft at the AASF	-0.016	0.005	0.002	***
Number of outstanding parts orders for H-60 helicopters	0.008	0.002	0	***
Number of outstanding parts orders, excluding H-60 helicopter orders	0	0.001	0.547	
Total number of days spent waiting for outstanding H-60 helicopter parts orders	0	0	0	***
Total number of days spent waiting for outstanding parts orders, excluding H-60 helicopter orders	0	0	0.207	

Adjustment variable	Coefficient	Standard Error	p-value	
Number of H-60 helicopter pilots at the customer unit	0.002	0	0	***
Number of mechanics at the customer unit	0.004	0	0	***
Number of backshop maintainers at the customer unit	-0.018	0.001	0	***
Indicator for a customer unit mobilization or deployment in 1 month or less	0.037	0.014	0.009	***
Indicator for a customer unit mobilization or deployment in 3 months or less	-0.005	0.014	0.739	
Indicator for a customer unit mobilization or deployment in 6 months or less	0.031	0.014	0.025	**
Indicator for a customer unit mobilization or deployment in 12 months or less	-0.075	0.009	0	***
Indicator for an helicopter deployment in 1 month or less	-0.018	0.025	0.46	
Indicator for an helicopter deployment in 3 month or less	-0.085	0.027	0.002	***
Indicator for an helicopter deployment in 6 month or less	0.001	0.022	0.973	
Indicator for an helicopter deployment in 12 month or less	0	0.01	0.976	
Helicopter prior month hours flown	-0.002	0	0	***
Mean helicopter hours flown in prior 3 months	-0.002	0	0	***
Helicopter prior month airframe hours	0	0	0.423	
Number of faults in spell	-0.076	0.001	0	***
Number of unique LDA topics	0.966	0.002	0	***
Indicator for a fault spell during phase maintenance	-0.721	0.012	0	***
Indicator for HH-60A Pave Hawk	0.518	0.033	0	***
Indicator for HH-60L Pave Hawk	-0.059	0.017	0.001	***
Indicator for HH-60M Pave Hawk	0.24	0.012	0	***
Indicator for UH-60L Black Hawk	-0.018	0.004	0	***
Indicator for UH-60M Black Hawk	0.015	0.009	0.093	*
Indicator for fiscal year 2011	-0.185	0.009	0	***
Indicator for fiscal year 2012	-0.107	0.007	0	***
Indicator for fiscal year 2013	-0.142	0.006	0	***
Indicator for fiscal year 2014	-0.012	0.005	0.028	**
Indicator for fiscal year 2016	-0.008	0.005	0.134	
Indicator for fiscal year 2017	-0.016	0.007	0.014	**
Indicator for fiscal year 2018	0.129	0.007	0	***
Indicator for fiscal year 2019	0.326	0.007	0	***

Adjustment variable	Coefficient	Standard Error	p-value	
Indicator for fault spell beginning on a Friday	-0.052	0.004	0	***
Indicator for fault spell beginning on a Monday	0.163	0.004	0	***
Indicator for fault spell beginning on a Saturday	0.374	0.006	0	***
Indicator for fault spell beginning on a Sunday	0.323	0.007	0	***
Indicator for fault spell beginning on a Thursday	-0.019	0.003	0	***
Indicator for fault spell beginning on a Tuesday	0.033	0.003	0	***
Indicator for fault spell beginning during December, January, or February	0.028	0.004	0	***
Indicator for fault spell beginning during September, October, or November	0.035	0.004	0	***
Indicator for fault spell beginning during June, July, or August	-0.003	0.003	0.374	

Note:
* = p-value less than 0.1;
** = p-value less than 0.05;
*** = p-value less than 0.01.

Table B-2. Table of Estimates from Section 5.B.1

Adjustment Variable	Coefficient	Standard Error	p-value	
(Intercept)	4.636	0.195	0.000	***
MilTech mechanics	**-0.010**	**0.003**	**0.000**	*****
MilTech backshop maintainers	0.014	0.004	0.000	***
TempTech mechanics	0.005	0.004	0.282	
TempTech backshop maintainers	0.011	0.009	0.216	
ADOS mechanics	-0.009	0.005	0.093	.
ADOS backshop maintainers	0.033	0.014	0.018	*
Man hours worked by traveling teams at the AASF	0.000	0.000	0.899	
MilTech mechanics mobilized, deployed, or on leave	-0.006	0.004	0.093	.
MilTech backshop maintainers mobilized, deployed, or on leave	0.009	0.005	0.080	.
Fraction of AASF maintainers mobilized or deployed in current month	-0.069	0.178	0.697	
Fraction of AASF maintainers mobilized or deployed in 1 month	-0.274	0.189	0.147	
Fraction of AASF maintainers mobilized or deployed in 3 months	0.224	0.158	0.156	
Fraction of AASF maintainers mobilized or deployed in 6 months	-0.032	0.142	0.821	
Fraction of AASF maintainers mobilized or deployed in 12 months	0.023	0.101	0.818	
Mean NMC% of AASF’s H-60 helicopters in the prior month	-0.024	0.067	0.719	
Mean NMC% of AASF’s H-60 helicopters in the prior 3 months	0.272	0.082	0.001	***
Mean NMC% of AASF’s AH-64, CH-47, and OH-58 helicopters in the prior month	-0.071	0.065	0.271	
Mean NMC% of AASF’s AH-64, CH-47, and OH-58 helicopters in the prior 3 months	0.197	0.106	0.062	.
Mean hours flown of AASF’s helicopters in the prior month, excluding UH-72 Lakotas	0.001	0.001	0.528	
Mean hours flown of AASF’s helicopters in the prior 3 months, excluding UH-72 Lakotas	0.000	0.000	0.955	
Mean airframe hours of AASF’s helicopters in the prior month, excluding UH-72 Lakotas	0.000	0.000	0.959	
Number of H-60 helicopters at the AASF	0.003	0.003	0.209	
Number of AH-64, CH-47, and OH-58 helicopters at the AASF	-0.004	0.003	0.228	
Number of UH-72 Lakotas at the AASF	0.008	0.006	0.199	
Indicator for any fixed wing aircraft at the AASF	-0.017	0.020	0.398	
Number of outstanding parts orders for H-60 helicopters	0.008	0.004	0.053	.
Number of outstanding parts orders, excluding H-60 helicopter orders	0.000	0.001	0.825	
Total number of days spent waiting for outstanding H-60 helicopter parts orders	0.000	0.000	0.025	*

Adjustment Variable	Coefficient	Standard Error	p-value	
Total number of days spent waiting for outstanding parts orders, excluding H-60 helicopter orders	0.000	0.000	0.682	
Number of H-60 helicopter pilots at the customer unit	0.002	0.002	0.462	
Number of mechanics at the customer unit	0.004	0.002	0.021	*
Number of backshop maintainers at the customer unit	-0.018	0.005	0.000	***
Indicator for a customer unit mobilization or deployment in 1 month or less	0.038	0.057	0.501	
Indicator for a customer unit mobilization or deployment in 3 months or less	-0.004	0.056	0.936	
Indicator for a customer unit mobilization or deployment in 6 months or less	0.030	0.046	0.518	
Indicator for a customer unit mobilization or deployment in 12 months or less	-0.074	0.033	0.026	*
Indicator for an helicopter deployment in 1 month or less	-0.021	0.070	0.767	
Indicator for an helicopter deployment in 3 month or less	-0.084	0.061	0.166	
Indicator for an helicopter deployment in 6 month or less	0.000	0.060	0.999	
Indicator for an helicopter deployment in 12 month or less	0.002	0.042	0.961	
Helicopter prior month hours flown	-0.002	0.001	0.003	**
Mean helicopter hours flown in prior 3 months	-0.002	0.001	0.095	.
Helicopter prior month airframe hours	0.000	0.000	0.754	
Number of faults in spell	-0.076	0.003	0.000	***
Number of unique LDA topics	0.966	0.011	0.000	***
Indicator for a fault spell during phase maintenance	-0.721	0.060	0.000	***
Indicator for HH-60A Pave Hawk	0.514	0.159	0.001	**
Indicator for HH-60L Pave Hawk	-0.061	0.083	0.461	
Indicator for HH-60M Pave Hawk	0.237	0.056	0.000	***
Indicator for UH-60L Black Hawk	-0.018	0.018	0.313	
Indicator for UH-60M Black Hawk	0.016	0.042	0.709	
Indicator for fiscal year 2011	-0.183	0.037	0.000	***
Indicator for fiscal year 2012	-0.108	0.032	0.001	***
Indicator for fiscal year 2013	-0.143	0.028	0.000	***
Indicator for fiscal year 2014	-0.012	0.026	0.640	
Indicator for fiscal year 2016	-0.007	0.025	0.770	
Indicator for fiscal year 2017	-0.015	0.029	0.600	
Indicator for fiscal year 2018	0.130	0.030	0.000	***

Adjustment Variable	Coefficient	Standard Error	p-value	
Indicator for fiscal year 2019	0.328	0.033	0.000	***
Indicator for fault spell beginning on a Friday	-0.052	0.018	0.004	**
Indicator for fault spell beginning on a Monday	0.163	0.019	0.000	***
Indicator for fault spell beginning on a Saturday	0.374	0.031	0.000	***
Indicator for fault spell beginning on a Sunday	0.323	0.032	0.000	***
Indicator for fault spell beginning on a Thursday	-0.019	0.016	0.224	
Indicator for fault spell beginning on a Tuesday	0.033	0.015	0.033	*
Indicator for fault spell beginning during December, January, or February	0.028	0.016	0.087	.
Indicator for fault spell beginning during September, October, or November	0.035	0.017	0.045	*
Indicator for fault spell beginning during June, July, or August	-0.003	0.016	0.842	

Note:
* = p-value less than 0.1;
** = p-value less than 0.05;
*** = p-value less than 0.01.

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Appendix C.
Recommendation: Allow Hiring Title 5 Federal Civilians at the TASM-G

The TASM-G has access to many sources of labor including MilTechs, AGRs, ADOS, and contractor support. The IDA team recommends allowing TASM-Gs the authority to hire Title 5 federal civilians, primarily in place of civilian contractors, and also to fill vacancies in markets where recruiting additional MilTechs is especially difficult. The intent of this recommendation is to allow the TASM-Gs experiencing difficulty filling their MilTech positions greater flexibility in the labor they employ, not to force the TASM-Gs to use Title 5 federal civilians. There are four reasons for this recommendation.

First, allowing the TASM-G to hire Title 5 federal civilian broadens the mechanic applicant pool and would therefore allow the TASM-Gs to be more selective when hiring. At present, TASM-Gs can only hire ARNG members from within their state.[92] This can be especially difficult for TASM-Gs in small states, such as Connecticut, where it is not unreasonable to live and work in a state different than the state the ARNG member drills in. For example, an individual could live in Groton, CT, work at the TASM-G, but drill in Rhode Island.

Second, Title 5 federal civilians can partially substitute for contract maintainers.[93] Substitution can conserve resources since contract maintainers must incur redundant overhead costs such as providing their own tools, equipment, and management. In addition, contracts have uncertainties due to continuing resolutions, change over in contracting company, and breaks in contract support due to a new contract being protested.

Third, ARNG members who leave the ARNG are no longer eligible for MilTech, AGR, or ADOS positions. Those individuals are at a point in their career where they have a large amount of valuable experience (especially so for those retiring). The TASM-G cannot retain those individuals. If the TASM-G can hire Title 5 federal civilians, then the TASM-G can retain experienced individuals that leave the ARNG. In addition, Title 5 federal civilians do not necessarily need to deploy and thus can provide continuity of experience stateside during a unit deployment.

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92 Exceptions can be made for ARNG members, but they involve inter-state ARNG agreements. Contractors can also be from out of state.

93 The substitution is partial because contractors can only be used for not inherently governmental work while Title 5 federal civilians can be used for governmental or non-governmental work.

Fourth and finally, hiring FTS under Title 5 can make MilTech positions available elsewhere in the TASM-G or throughout the state if Title 5 positions are added in addition to MilTech positions.

There are three potential reasons for concern in allowing the TASM-G to hire Title 5 federal civilians:

- Such a policy could reduce prior service recruiting into the ARNG because potentially fewer FTS positions would be available for ARNG members. The potential for getting a FTS position can be a large incentive for prior service to join the ARNG.
- There could be a decrease in both the number and the average experience of deployable TASM-G personnel.
- FTS positions that require ARNG membership are a retention incentive for the ARNG. If individuals were not required to maintain ARNG membership for their FTS position, then they might leave the ARNG.

The first two concerns against Title 5 are valid if Title 5 federal civilians are used to substitute not just for contractors, but for MilTechs and AGRs as well. There are three options to help mitigate this:

- A decrease in funding for contractors can coincide with the new ability to hire Title 5 federal civilians. This option is not preferred because it forces the TASM-G to substitute contractors for Title 5 federal civilians (for not inherently governmental work), rather than allowing the TASM-G greater flexibility to hire who they want.[94]
- A more preferred option is to simply cap the total number of Title 5 federal civilians the TASM-G can employ at any given time.[95]
- Title 5 federal civilians could be hired as a part of the expeditionary civilian workforce, under DTM-17-004 where they can be deployed.[96] The third option can coincide with either of the first two.

Among the other concerns are inconsistencies with the original five criteria for determining which MilTech positions to convert to Title 5, loss of managerial flexibility, and general distaste for Title 5 among senior leadership. The ARNG created an Adjutants General Tiger Team to create

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94 An A-76 study might need to be performed to assess the functions and which should be Title 5 federal civilian and what should be contracted. DODD 1100.4 and DODI 1100.22 provide directive and instruction for manpower management (including civilians).

95 Ideally, a position would be flexibly listed at MilTech or Title 5 and if the applicant is eligible for a MilTech position, they must be hired as a MilTech. However, available positions cannot currently be listed in such a manner.

96 Traditionally, the expeditionary civilian workforce deployments are individual positions and are not automatically a part of a unit mobilization. Thus, the Title 5 federal civilian may have to apply and be accepted into the expeditionary civilian workforce before joining the unit for a mobilization.

criteria for determining which positions would be excepted from conversion to Title 5. The team came up with five criteria. The most relevant of the five are (paraphrased): 1) the position has an affiliated wartime requirement or requires military skills and the technician performs civilian work, trains at, and deploys with the same unit; 2) the position is wage grade (WG); 3) the technician performs administration and training or maintenance and repair; 4) any position which requires current military skills and knowledge as outlined in DODD 1100.22; and 5) the position is a key advisor to the Adjutant General with regard to recommendations for engagement of National Guard capabilities. MilTech mechanics at the TASM-G satisfy criteria 1, 2, and 3. The first criterion is to maintain deployability and overseas capabilities, which was addressed in the previous paragraph. The purpose of the second two is not immediately clear to the IDA team and despite attempts to gain clarification, none was given.

The ability to hire Title 5 federal civilians would allow the TASM-G greater flexibility to hire experienced personnel to accomplish their stateside mission while, hopefully, not overly degrading their deployability. This policy could be implemented gradually to observe the (possibly unanticipated) spillover effects, such as the effect on retention in the ARNG.

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Appendix D.
Additional Information

Helicopter types

The CH-47 Chinook is a twin-engine, tandem rotor, heavy-lift helicopter that entered service in 1962. The primary mission of the CH-47 Chinook is transporting artillery, ammunition, personnel, and supplies on the battlefield. It can also support rescue, aeromedical, parachuting, aircraft recovery, and special operation missions. The CH-47 Chinook—in its CH-47D and CH-47F variants—accounts for 14% of the ARNG helicopter fleet during the period of analysis. Figure D-1 depicts a CH-47 Chinook undergoing maintenance.

Source: IDA.

Figure D-1. A CH 47 Chinook Undergoing Maintenance.

The AH-64 Apache is a twin-turboshaft attack helicopter that entered service in 1986. The primary missions of the AH-64 Apache are armed reconnaissance, close combat, mobile strike, and vertical maneuver missions when required, in day, night, obscured battlefield, and adverse weather conditions. The AH-64 Apache accounts for 6% of the ARNG helicopter fleet. The ARNG has reduced its fleet of AH-64 helicopters from 158 at the end of fiscal year 2015 to 73 at the end of fiscal year 2018. The AH-64 Apaches have two variants over the period of analysis: AH-64A and AH-64D.

The UH-72 Lakota is a twin-engine light utility helicopter than entered service in 2007. The primary mission of the UH-72 Lakota is to provide a flexible response to homeland Security requirements such as search and rescue operations, reconnaissance and surveillance, and medical evacuation (MEDEVAC) missions. The UH-72 Lakota is deployed only to non-combat environments such as supporting the United States southwest border. Unlike the other ARNG helicopter platforms, the UH-72 is maintained by a mix of contract and ARNG support in a program called "hybrid maintenance." The UH-72 Lakota accounts for 15% of the ARNG helicopter fleet.

The OH-58 Kiowa was a single engine reconnaissance helicopter that entered service in 1969 and left ARNG service in 2017. The primary mission of the OH-58 Kiowa was reconnaissance, security, target acquisition and designation, command and control, light attack and defensive air combat missions in support of combat. The OH-58 Kiowas are present in three variants over the period of analysis: OH-58A, OH-58C, and OH-58D.

Appendix E. Illustrations

Figures

Tables

Appendix F.
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Appendix G.
Abbreviations

AAFA	Army Aviation Flight Activity
AAOF	Army Aviation Operation Facility
AASF	Army Aviation Support Facility
AATS	ARNG Aviation Training Site
ADOS	Active Duty Operational Support
AFTP	Additional Flight Training Period
AGR	Active Guard and Reserve
ARNG	Army National Guard
ASL	Authorized Stock List
AT	Annual Training
ATP	Army Technical Publication
CCAD	Corpus Christi Army Depot
CMIS	Corporate Management Information System
CNA	Center for Naval Analyses
DA	Department of the Army
DA PAM	DA Pamphlet
DAG	Directed Acyclic Graph
DCPDS	Defense Civilian Personnel Data System
DOD	Department of Defense
EAATS	Eastern AATS
FTS	Full-Time Support
FMC	Fully Mission Capable
GAM	Generalized Additive Model
HAATS	High Altitude Aviation Training Site
IDA	Institute for Defense Analyses
IDT	Inactive Duty for Training
LAASF	Limited AASF
LMO	Logistics Management Officer
LOESS	Locally Estimated Scatterplot Smoothing
MAR	Missing at Random
MCAR	Missing Completely at Random
MC	Mission Capable
MCMC	Markov chain Monte Carlo
MDS	Mission Design Series
MICE	Multiple Imputation by Chained Equations
MilTech	Military Technician
MOS	Military Occupational Specialty
MSPB	Merit Systems Protection Board

MTOE	Modified Table of Organization and Equipment
NDAA	National Defense Authorization Act
NGB	National Guard Bureau
NGR	National Guard Regulation
NHST	Null Hypothesis Significance Test
NMC	Not Mission Capable
NMCM	NMC due to Maintenance
MNCS	NMC due to Supply
NMP	National Maintenance Program
OR	Operational Readiness
ORF	Operational Readiness Float
PLL	Prescribed Loading List
PMC	Partially Mission Capable
PMCM	PMC due to Maintenance
PMCS	PMC due to Supply
PPM	Progressive Phase Maintenance
RCMS-G	Reserve Component Manpower System - Guard
SAO	State Aviation Officer
SME	Subject Matter Expert
TDA	Table of Distributional Allowances
TempTech	Temporary Military Technician
TM	Technical Manual
USPFO	United States Property and Fiscal Officer
WAATS	Western AATS

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14. ABSTRACT

This Institute for Defense Analyses research quantifies the relationship between maintenance manpower investments and H-60 helicopter readiness in the Army National Guard (ARNG). Using causal econometric methods, IDA researchers find that increasing the number of military technician (MilTech) mechanics at ARNG Army aviation support facilities (AASFs) of all sizes reduces helicopter maintenance timelines to a statistically significant extent. Grouping faults into contiguous "fault spell" downtime events, we estimate that an additional MilTech mechanic decreases average fault spell duration by 0.7% to 1.1% (depending on baseline MilTech staffing levels). Downtime reductions were greatest for maintenance facilities with fewer initial MilTech mechanics. These downtime reductions accumulate over ARNG H-60 NMC resolution maintenance at the AASF level. We estimate that the addition of a single MilTech mechanic to each ARNG AASF would produce 23 to 30 additional mission capable (MC) hours per H-60 helicopter, or 3.2 additional ready helicopter years across the ARNG's fiscal year 2019 H-60 fleet. These results can provide targeted readiness-enhancing staffing recommendations appropriate for a resource constrained environment by informing placement of additional MilTech mechanics. Per additional ready H-60 helicopter year, we found that additional MilTech manpower is a more cost-effective way to improve readiness than borrowing or buying additional UH-60M Black Hawks.

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