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Improved Modeling of Maintenance for Future Vertical Lift

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Abstract: The Future Vertical Lift (FVL) Cross Functional Team (CFT) required analysis on the sustainment performance of FVL aircraft operating in Multi-Domain Operations (MDO). A study from last year forecasted the sustainment performance of FVL's Future Attack Reconnaissance Aircraft (FARA) based upon historical performance of the enduring AH-64 Apache infused with emerging technologies. This study improved last year's model by refining key assumptions. First, a Forward Maintenance Team in MDO conducted limited maintenance that was constrained by an austere environment. Second, the assumption of constant component failure rates was updated with increase hazard rates to reflect fatigue in mechanical systems like the transmission and rotors. Third, technological risk was captured by accounting for the uncertainty associated with infused technologies based on the Technology Readiness Level. Finally, the historical failure rates of the enduring fleet of AH-64, UH-60, and CH-47 aircraft guided reliability forecasts for FARA increments over its life cycle.

Keywords: Maintenance Free Operating Period, Limited Maintenance Operating Period, Future Vertical Lift

1. Introduction

The Future Vertical Lift (FVL) program will field a new fleet of aircraft to better meet the needs of a modern U.S. Army in Multi-Domain Operations (MDO). The new doctrine called for sustained forward operations less encumbered by maintenance that is the objective of a Maintenance Free Operating Period (MFOP) strategy. Through simulation of the current fleet, previous research provided the CFT with the knowledge that the strict adherence to an MFOP on the order of 100 hours was likely unattainable, as the AH-64E averaged an MFOP of less than 10 flight hours (Bellocchio, 2021). This year's research sought to add more information to the simulation to improve prediction accuracy of FVL performance incorporating technology improvements, lifespan reliability growth, a mobile Forward Maintenance Team, and improved hazard rates expected with FVL to enable the CFT to tailor requirements for FVL.

2. Background Research

A literature review covering multiple topics including the current U.S. Army attack aviation aircraft system (AH-64E) and new technologies that are expected to be part of the FVL aircraft was conducted to gain a better understanding of possible simulation improvements. More specifically, the research covered the current forward maintenance procedures for the AH-64, progressive phase maintenance attempted on previous military rotorcraft, commercial aircraft operators' best maintenance practices, new rotorcraft materials that are lighter and more reliable, and the implementation of modeling simulation on changes from early (AH-64A) to later (AH-64E) models.

2.1 Forward Maintenance

Army planners are seeking an MFOP to satisfy MDO needs that is longer than the enduring fleet can achieve (DA, 2007; Bellocchio et al., 2021). The new doctrine requires the Forward Maintenance Teams (FMT) to repair aircraft in an austere environment under a constrained time and logistical footprint (parts, equipment, manpower, and facilities). This research captured the impacts of improvement of maintenance practices, better aircraft maintainability, the implementation of predictive maintenance, an FMT optimized for a given MFOP.

2.2 Progressive Phase Maintenance and Maintenance Steering Group 3

Progressive Phase Maintenance (PPM) is a maintenance approach for rotorcraft that has successfully increased the mean time between failures by 10% (Carpenter, 2020). Under PPM, the aircraft maintenance may be conducted early enough to provide the maintainer flexibility to conduct repairs at the most convenient time that balances maintenance capacity and operational demands. FVL aircraft can utilize progressive maintenance in the Limited Recovery Period (LRP), discussed in detail later, if time and resources allow it, to gain the advantages of PPM. Another option to improve maintenance practices is to incorporate modern technologies and best practices currently used in the commercial industry, including creating a program similar to the Maintenance Steering Group-3 (MSG-3) in support of MFOP. Applying MSG-3 could provide many benefits, including a 10% improvement to scheduled maintenance, a 25% improvement to MTBF (Carpenter, Alexander, Jonas, & Smith, 2020). Lastly, prognostics can be incorporated into FVL to improve fault detection. Prognostics play a heavy role in commercial aircraft maintenance and are used to automatically predict faults as reported in structural health monitoring systems capable of detecting 70% of all faults in an airplane (Boller & Buderath, 2007). The incorporation of PPM, MSG-3 and prognostics into the U.S. Army FVL program are all options that could lead to marked improvements in aircraft maintenance to improve reliability, raise availability, and increase the MFOP.

2.3 Hazard Rate and Fatigue

A large part of modeling reliability of mechanical systems is accounting for the fatigue of components. Cyclic loading causes components to reach a fatigue level, leading to failure (O' Connor & Kleyner, 2012). Aircraft experiences vibration and cyclic loading that result in component fatigue. The hazard rate identifies the probability an item fails over time (Jardine & Tsang, 2013). The fatigue phenomenon identifies the connection of both ideas, as stress continues, fatigue can be modeled using the hazard function, $h(t)$, (Hsu, Wang, & Liu, 2002) as

$$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{1}$$

where β is the Weibull shape parameter, η is the scale parameter, and t is the time. Components in the rotor, powerplant, powertrain, and structures experience an increasing hazard rate with a shape greater than 1 and are the best candidates for predictive maintenance to identify impending failure.

2.4 Modeling Research

The AH-64's evolution over its 40 years of operation may hint at the evolution of FVL through its life cycle. The Mean Time Between Failure (MTBF) as compiled from maintenance data in the Aviation System Assessment Program (ASAP) benchmarked the progression of the AH-64 from the increment 1 (AH-64A) to increment 2 (AH-64D) to increment 3 (AH-64E). Since FVL prototypes are still under fabrication, there are no trends to reference. The AH-64 served as a surrogate for FVL. The research explored the performance of FVL as modeled in a discrete event simulation if it followed the same trends as measured in the AH-64.

3. Methods

3.1 Screening the Limited Recovery Period

Previous work determined that current MFOP goals could only be achieved by extraordinary investment in component reliability. To reduce cost and program risk, the authors propose the concept of a Limited Maintenance Operating Period

(LMOP). An LMOP concept contains a series of shorter, attainable MFOPs separated by Limited Recovery Periods (LRP) as shown in Figure 1. The LRPs provide FMTs the ability to address Essential Maintenance Actions (EMAs) forward with minimal disruption to operations. The previous sustainment model assumed all EMAs could be performed by FMTs in forward operating environments; however, the assumption is unrealistic because many EMAs require access to special equipment or specialized maintainers are located at higher echelon facilities. The previous model was overpredicting the maintenance capability within the MFOP resulting in an inaccurate availability rate. The assumption was corrected by quantifying the percentage of essential maintenance actions that are feasible in the LRP.

A data set of AH-64 maintenance actions was organized by their 28-distinct subsystems and ordered by precedence of subsystems that produce the most EMAs. A Pareto analysis identified the top 11 subsystems that accounted for 79.1% of the total EMAs. A sample of the top 10 EMAs from each of these subsystem groups, for a total of 110 EMAs, were evaluated to determine the feasibility of correcting the maintenance fault within a forward operating environment. This analysis focused purely on the EMA corrective actions and not the prerequisite tasks or the post-fix tasks, due to expertise gaps present in the team. Although incomplete, the analysis provided a better estimate of FMT capability. The method of evaluating the most frequent EMAs was chosen to identify the number of maintainers, skillsets, tools, and components necessary in an FMT to solve the most consistent EMAs while avoiding any EMAs that limit mobility.

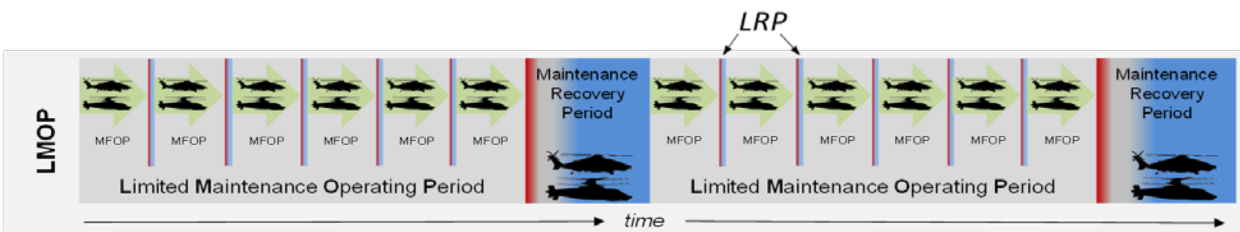


Figure 1. Concept of the Limited Maintenance Operating Period

3.2 Weibull Hazard Rate Analysis

In addition to adjusting the percentage of EMAs performed in the LMOP, this research evaluated the hazard rate of aircraft components to predict failures more accurately. The previous FVL maintenance model used a constant failure rate to simulate how often subcomponents fail. Research on aircraft components showed repeated use and loading results in collective fatigue, ultimately lead to an increased failure rate over time (O' Connor & Kleyner, 2012). An analysis was conducted using AH-64 data to determine the impact of subcomponent age on the airframe's hazard rate. The null hypothesis for the experiment was the Weibull distribution would identify a shape parameter greater or equal to 1.0, indicating components wear-out at increasing rates over time. The data included 18 serial-numbered and tracked components of the airframe with their calculated failure ages equal to the differences of the removal and install times. The majority of subcomponents were found to have a shape parameter greater than one, Then, based on these ages, the Weibull shape and scale parameters were fitted to each component. Using RStudio with the Weibull parameters, the authors took the subcomponents of the airframe, used 100,000 random variates of age, and fitted a Weibull distribution to all simulated points for all subcomponents. Figure 2 identifies a zoomed view of the distribution created from the superposition of subcomponents. The shape was calculated to be 0.43, which indicated airframe components would get healthier over time, contradicting fatigue reliability engineering research. This was an interesting result that reflects a superposition of subcomponent distributions does not necessarily capture the true behavior of a system.

After analyzing the overall Weibull distribution based on previously calculated parameters, there is no mathematical evidence to support the null hypothesis because the simulated Weibull shape does not follow fatigue and reliability engineering principles. The contradicting results is attributed to the limited data used to create the component fits that is censored by preventive removal before component failure. To generate better statistical models, the authors recommend recording the component age at failure. If a component is removed due to preventive maintenance, it should be run on a bench test to failure with the age then recorded. In the absence of this data, the authors recommend a shape parameter of 2. This provides for an increasing hazard rate that is more conservative than a normal distribution and improves on the original assumption of a constant failure rate.

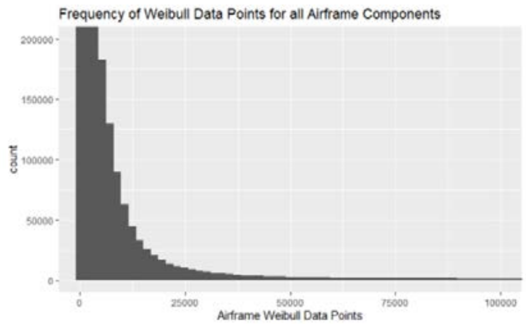


Figure 2. Histogram with all simulated Weibull data points for all airframe components.

3.3 Predicting Mean Time Between Failures from Increment 1 to Increment 3

An analysis was performed on historic rotorcraft growth from increment 1 to increment 3 to determine future FVL impacts on aircraft availability. The EMAs of the enduring fleet Army aircraft (AH-64, UH-60, and CH-47) were analyzed to determine their MTBF and predict those of FVL. Determining maintenance deficiencies of current rotorcraft is not only crucial to set requirements for the future, but their percent changes from their first to last increments can predict the maintenance of FVL over its life and increase the ability to shape the LRP requirements. The MTBF of each rotorcraft and all its subcomponents were modeled graphically as linear trend lines from increment 1 to increment 3.

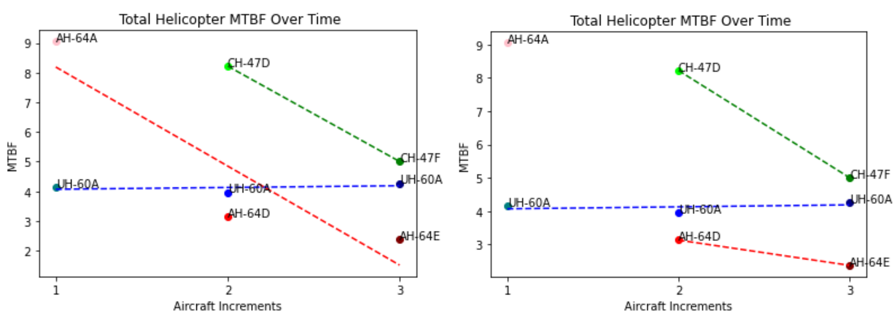


Figure 3. MTBF of AH-64, UH-60, CH-47 Models from Increment 1 to Increment 3

All rotorcraft were scored by logging what maintenance action took place and its subsystem. The graph on the left in Figure 3 shows trend lines from increment 1 to increment 3 for all increments evaluated. Data from the AH-64A model, or increment 1, and was estimated using artificial intelligence (AI) and is not fully validated. Similarly, the CH-47D model was 75% scored through AI. As a result, the graph on the right in Figure 3 shows the trendlines for the data that is likely more accurate due to complete human scoring of the maintenance actions. From the graphs, the percent change from increment to increment determines which subcomponent maintenance has increased or decreased overtime, providing the ability to predict the likeliness of similar results within FVL.

3.4 Determining Confidence Intervals for the Effects of Mature Technologies Based on Technology Readiness Level

FVL manufacturers are incorporating thirteen key technologies that improve sustainment performance. Each provide a benefit to at least one of the following maintenance statistics: Mean Time to Repair (MTTR), Fault Detection/Identification (FD/FI), MTBF, and Scheduled Maintenance (SM). A study by Wichita State (Carpenter et al., 2020) quantified technology improvement or degradation in the above metrics. These technology factors, however, are not absolute. To model uncertainty, a Weibull distribution was created for the percentage changes where the location parameter, γ, is the technology's percent change. (Kirby, 2001) gives the scale of the technologies Weibull distribution as a function of TRL as

$$\eta = |0.3\gamma| - (TRL - 1)\left(\frac{|0.3\gamma| - |0.05\gamma|}{8}\right). \quad (2)$$

The TRL of a technology is determined by quantifying its maturity relative to FVL using the Department of Defense TRL scale (DoD, 2010). The γ is the impact is the improvement/degradation percentage of a maintenance statistic (e.g., composite materials improve MTBF by 25% so γ is 0.25 for this technology). It is also important to note that there are two versions of this equation; this is the "more is better" version and is used when a technology improves a maintenance statistic. The only difference in the "less is better" equation is that (TRL – 1) becomes (9 – TRL). For each iteration that a technology is applied to the AH-64 model, a random sample is taken from its Weibull distribution. These random samples are then combined and used to create a confidence interval for the probability of MFOP success across the desired period. Figure 4 displays dashed lines on either side of simulation results, representing the 95% confidence interval for MFOP Probability of Success as the mature technologies are applied in each increment.

4. Results and Discussion

Changing the capabilities of the FMT in the LRP had the most significant effect on the achieved availability. The relationship between maintenance ratio and achieved availability is such that the variability in achieved availability increases as the maintenance ratio decreases. Achieved availability consists of the mean time between EMAs divided by the total time in the simulation, and the Maintenance Ratio is the number of Maintenance Man Hours (MMH) per flight hour.

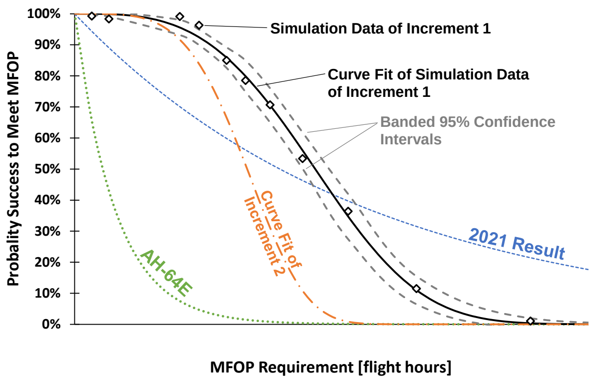
When looking at Weibull distributed data for the airframe subcomponent, the original model's constant hazard rate is not supported by fatigue and reliability engineering, and therefore, is an inaccurate rate to model reliability for FVL. To improve the model that simulates the LRP, the hazard rate should be above 1.0, as research identifies components fail increasingly over time. For future analysis, the Army needs to provide increasingly detailed data that will allow components to reach their full life span, and then Weibull data can be simulated to create an accurate hazard rate. A similar simulation with reliable data will provide information for FVL and should be a topic for future investigation.

After developing the graphs in Figure 3, the percent changes from increment to increment were determined for each subcomponent of the aircraft. Three rotorcrafts were evaluated to determine if the changes found were across aviation or specific airframes. The results for the top three producing EMA subcomponents can be found in Table 1 with confidence on results expressed as colors. Trends consistent between airframes are noted as useable while trends that conflicted between airframes or were heavily influenced by AI scoring are rated as doubtful or unusable.

Table 1. Top Maintenance Driver Percent Change in MTBF Between Increments

WUC/Nomenclature	Apache (D to E)	Black Hawk (A to M)	Chinook (D to F)
05 Rotor System	-30.73%	-2.49%	81.18%
02 Airframe	-39.08%	1.01%	46.52%
06 Drive System	-29.75%	11.39%	-62.51%
Usable Results	Doubtful Results	Unusable Results	

The differences between increments were incorporated into the simulation. Figure 4 shows the results of the model improvements including the increased hazard rate, Weibull-fit TRL confidence intervals, and predicted impacts of FVL growth from increment 1 to increment 3. The research conducted in this study provides a more accurate simulation model to predict the MFOP probability of success across MFOP flight hour requirements.



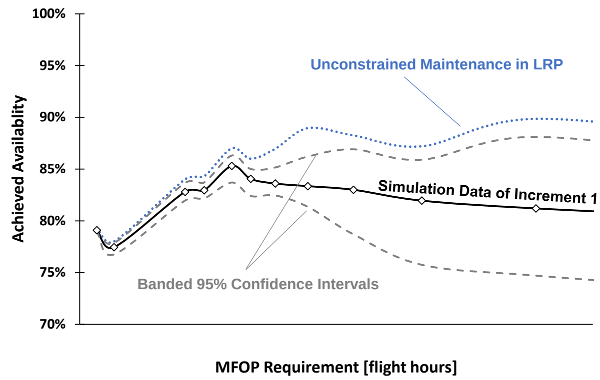


Figure 4a. Simulation Result of MFOP Success. Figure 4b. Simulation Result of Achieved Availability.
Flight hours are removed for controlled technology distribution reasons.

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