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Evaluating a Maintenance Free Operating Period for Future Vertical Lift

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Author Note: Cadets NaVonte Dean, Dominic Distefano, Mitchell McHugh, and Patrick Oursler are members of West Point's Class of 2021. Upon graduation, they will commission into the U.S. Army as a Second Lieutenants in the Air Defense Artillery, Armor, Field Artillery, and Aviation branches, respectively. The cadet team was advised by Dr. Eugene Lesinski and Lieutenant Colonels Kathryn Pegues of USMA's Department of Systems Engineering and Andrew Bellocchio of USMA's Department of Civil and Mechanical Engineering.

Abstract: The Future Vertical Lift (FVL) Cross Functional Team (CFT) of the U.S. Army Futures Command required analysis on the integration of a maintenance free operating period (MFOP) into aviation operations to inform FVL requirements development and acquisition decisions. The selected Technology, Identification, Evaluation, and Selection (TIES) methodology explored the integration of MFOP strategy into aviation sustainment. TIES was used to develop a value model and cost model to rank MFOP enhancing activities. The value of an MFOP enhancing activity was modeled as a function of six performance metrics: Maintenance Free Operating Period (MFOP) duration, MFOP Success (MFOPS), Maintenance Ratio (MR), Achieved Availability, Maintenance Recovery Period (MRP) duration, and MRP Success (MRPS). The value and cost models used outputs from an Apache operation simulation developed in ProModel. Relative value was determined from feedback gathered on a stakeholder survey. Repair cost estimates were developed from the Maintenance Availability Data Warehouse database.

Keywords: Future Attack and Reconnaissance, Future Vertical Lift, Aircraft, Maintenance Free Operating Period (MFOP), Sustainment

1. Introduction

After having employed the Blackhawk, Apache, and Chinook helicopters for almost 40 years, the United States Army is updating its rotary-wing fleet, creating a new generation of state of the art systems (Gertler, 2020). These aircraft, comprising the enduring fleet, have become increasingly expensive to maintain and to upgrade to keep up with the new technologies of the advanced cyber-physical world. In FY 2017 alone, the Apache fleet incurred $1.71 million in operations and support (O&S) cost per aircraft (U.S. Government Accountability Office, 2020) while also not meeting mission capable goals. The U.S. Government spent a significant amount of money to maintain aircraft that were not readily available to support operations. Due to the mounting O&S costs and emergence of multi-domain operational needs for the rotor-wing fleet, the Department of Defense (DoD) initiated the Future Vertical Lift (FVL) program. The acquisition program was initiated to develop and procure vertical lift platforms that are lethal and survivable in the multi-domain battlespace (Rugen, Isaacson, & McLean II, 2021).

One way the FVL program sought to develop the vertical lift fleet was through improved sustainment efforts. Key initiatives of the FVL sustainment program are the reduction of the logistical footprint, improved operational and material availability, increased unit sustainment capabilities, and overall reduced life-cycle O&S cost (U.S. Army Aviation Center of Excellence 2020). To inform FVL development decisions to improve sustainment, Bellocchio recommended examining the effects of a maintenance free operating period (MFOP) strategy (Bellocchio, 2018). A MFOP is defined as a period during which the aircraft operates without the need for service beyond replenishment (Rugen, Isaacson, & McLean II, 2021). An MFOP-based strategy differs from current maintenance operations because the MFOP provides an assurance to the user that the aircraft will operate for a given duration without maintenance. Figure 1 depicts the MFOP-maintenance recovery period (MRP) cycle as a function of time. MFOP duration is measured in flight hours, and MRP duration is measured in maintenance man hours (MMH). Scheduled maintenance activities include any regularly planned maintenance that occurs at fixed time intervals (Bellocchio, 2018). All scheduled maintenance activities are consolidated into the MRP to avoid disruptions of flight operations.

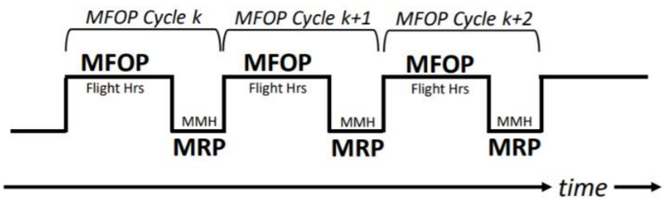


Figure 1. MFOP-MRP Cycles (Bellocchio, 2018)

The Army has not conducted significant analysis of the organizational benefit or relative cost of implementing MFOP and seeks understanding of the consequences of implementing a MFOP strategy. The purpose of this research was to analyze the impact of MFOP on sustainment operations and advise the FVL Cross Functional Team (CFT) on requirement thresholds for MFOP. The FVL CFT needs MFOP analysis to understand reasonable requirements that push the Future Attack Reconnaissance Aircraft (FARA) competitors to advance the state of the art while mitigating risk with attainable goals. This MFOP analysis could potentially inform changes to Army Aviation across Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel and Facilities, and Policy (DOTMLPF-P). To better inform key stakeholders, the FVL CFT directed the cadet capstone team to assess potential "MFOP activities" taking into account cost, schedule, performance, and feasibility risk and risk mitigation. An MFOP activity is any action, policy, technology, or knowledge that affects the duration of the operating period. This technical paper specifically discusses the methodology used to develop the value and costing model components needed to conduct analysis of MFOP activities on performance.

2. Methodology

The methodology used to complete this research effort was the Technology, Identification, Evaluation, and Selection (TIES) approach developed by Kirby and Mavris of the Georgia Institute of Technology (Kirby, 2001). In previous research, this approach was used to assesses the implementation of mature commercial technologies. The TIES methodology follows a logical flow of eight steps and may be iterative. A return to previous stages is necessary and acceptable with the receipt of new information. Figure 2 displays the eight step TIES process.

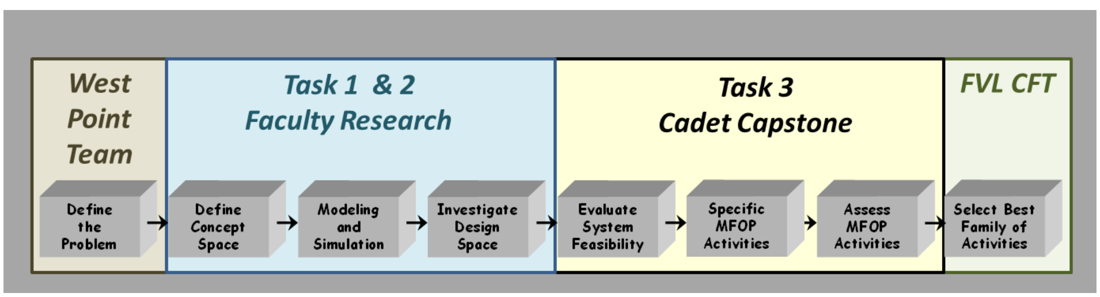


Figure 2. Technology, Identification, Evaluation, and Selection (TIES) Methodology Diagram

2.1 Define the Problem

To make informed sustainment acquisitions decisions for the FARA platform, the CFT seeks quantitative analysis on the costs and benefits of a MFOP strategy. Modeling and understanding the performance of FARA was a challenge because FARA is still in the initial phases of development. To perform the quantitative analysis, the capstone team estimated FARA performance using the Apache as a surrogate while integrating advanced technologies. The FVL program has several goals for optimizing performance, lethality, reach and sustainability, survivability, and affordability of the future fleet. The project, as specified by the client, centered on the sustainability of FARA as it is related to the implementation of an MFOP strategy.

2.2 Define Concept Space

To move forward with modeling and analysis and provide a useful recommendation to the client, the team first established boundaries for the project. The scope of this project is bounded by six categories: Data Source, Granularity, Platform, System Focus, Echelon, and Investment Options.

The "data source" category specifies what aviation component data is available and what will be used for modeling. This category spans historical data from the enduring fleet to predict future aircraft performance. For this study, the client directed that the team focus on analysis supporting FARA development. Therefore, the model used historical data from the last five years of the Apache (AH-64E), the enduring helicopter whose mission FARA will assume. The AH-64E based simulation serves as a surrogate model for future FARA analysis. Using recent enduring fleet data to develop failure, repair, and cost distributions provided a realistic foundation from which to build Army Aviation Maintenance simulation.

"Granularity" designates the level at which the data will be analyzed with the lowest level being each component and the highest level being the total system. This research effort performed analysis at the sub-systems level of the Apache. Data was provided for 28 subsystems include Airframe, Rotor System, and Fuel System. Modeling at the subsystem level identifies general areas of weakness where the FVL should invest resources to improve reliability.

"System focus" is the category of system design and operation being analyzed. The FVL project has several goals for optimizing performance, lethality, reach and sustainability, survivability, and affordability. The focus of this project, as specified by the client, was the sustainability of FARA as it relates to MFOP strategy implementation.

"Echelon" refers to the different hierarchical levels at which Army Aviation operates or the quantity of aircraft being modeled. This project modeled the maintenance of a single aircraft.

The final category of "Investment Options" included all of the possible maintenance strategies and technologies that could have had an impact on MFOP ranging from current maintenance practices by the Army and commercial aviation to future technologies under development. "Investment Options" was the full list of alternatives that the capstone team considered for improving this system. Ultimately, the capstone team narrowed the potential investments areas to thirteen technologies specified in the FirePoint Study conducted by Wichita State University (Carpenter, Alexander, & Jonas, 2020). Some examples of the technologies researched in the FirePoint study are Modular Design, Composite Materials, and Predictive Analytics. The team focused on these technologies because they have mature technology readiness levels (TRLs) and have the potential to be incorporated in a FARA prototype. The FirePoint study also quantified the sustainment performance of the technologies with respect to operational availability. The capstone team sought to quantify sustainment performance with respect to an MFOP strategy. Table 1 contains a full list of the selected technologies and their respective multiplicative effect on the simulation parameters.

Table 1. FirePoint Technologies Effects Matrix with Simulation Multipliers to Vary AH64 MFOP Model Parameters

Capstone Team Effects Matrix	**Simulation Multiplier**			
FirePoint Technology	**Mean Time to Repair (MTTR)**	**Fault Detection / Identification (FD/FI)**	**Mean Time Between Failure (MTBF)**	**Scheduled Maintenance (SM)**
Advanced NDI techniques	0.75	0.50	-	0.50
Electronic Maintenance and Health Monitoring Systems	-	0.50	-	0.50
Integrated Engine Vibration Monitoring & Control	-	0.50	1.10	0.50
Integrated Active Structural Vibration Monitoring & Control	-	0.50	1.10	-
Digital Twin w/ Data	0.95	-	1.05	0.90
Fly-by-Wire	0.90	0.90	1.10	-
Composite Materials	-	1.10	1.25	-
Digital Maintenance and Work Instructions	0.90	0.85	-	0.90
Common Support Tools	0.75	0.75	-	-
Progressive Maintenance			1.10	0.90
MSG-3 Approach	-	-	-	0.90
Predictive Analytics	-	1.0	1.05	-
Modular Design	0.75	0.80	-	0.87

2.3 Evaluate System Performance

The capstone team evaluated alternative MFOP enhancing activities using value and cost. These evaluations required models to reflect stakeholder interests and historical data. The value model assessed alternative MFOP enhancing activities based on the utility they provided to the stakeholder. The costing model used historical AH-64 data to return relative cost estimates of implementing an alternative MFOP enhancing activity. This section details the development of the value and costing models.

2.3.1 Value Model Development

The team developed a value model to assess the utility provided by each investment alternative. This process included systems analysis, requirements identification, and stakeholder analysis. Developing an effective value model required both qualitative and quantitative analysis (Parnell, Driscoll, & Henderson, 2011).

To assess the relative value of investments on MFOP performance, the team first created a qualitative model to identify the metrics used to assess value and organize them using the value hierarchy technique (Parnell, Driscoll, & Henderson, 2011). The team identified the four main functions of the Army Aviation System as Operate Aircraft, Maintain Aircraft, Monitor System Health, and Manage Maintenance Activities. Each function has an associated objective that indicates if the system is performing the function. Finally, the lowest level of the value hierarchy identifies value measures, the actual metrics of system performance. The value measures translate to variables used in the quantitative value model. Initially, the team identified eleven value measures but later narrowed it down to the six most important specified by the clients in a stakeholder feedback survey. The final value measures included MFOP duration, MFOPS, MRP duration, MRPS, MR, and Achieved Availability.

The stakeholders provided their opinion for how impactful each value measure was to the system and compared the value measures on a relative scale in the stakeholder feedback survey. The survey results were compiled and analyzed to develop the function for the value model. The relative importance, or global weights, of each value measure was determined by comparing score assigned to each value measure by each stakeholder to the value measures' respective average scores. Figure 3 shows the results from the stakeholder survey and the calculated global weights.

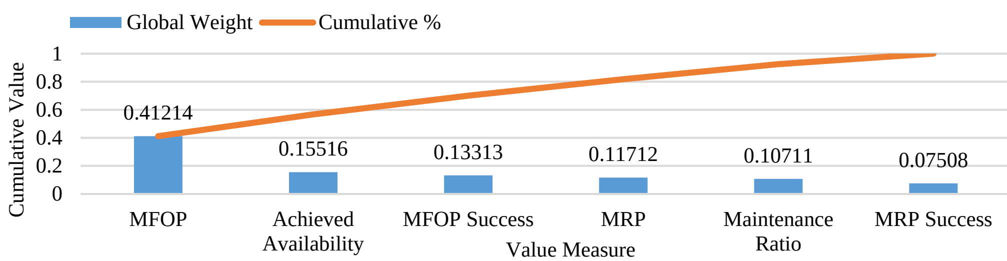


Figure 3. Global Weights and Cumulative Value Computed from Stakeholder Feedback Survey Results

The graph illustrates how relative weights of each value measure contribute to the total value of the future implementation of an MFOP Activity, or alternative. The relative weights of each value measure were then translated to an equation to use as the final value model (Equation 1). The implementation of different alternatives will have impacts on the system represented by the inputs of this value model. Those inputs are iterated through the value model to assess and compare alternatives.

$$Value = (0.41)MFOP + (0.16)A_A + (0.13)MFOPS + (0.12)MRP + (0.11)MR + (0.07)MRPS \tag{1}$$

2.3.2 Cost Model Development

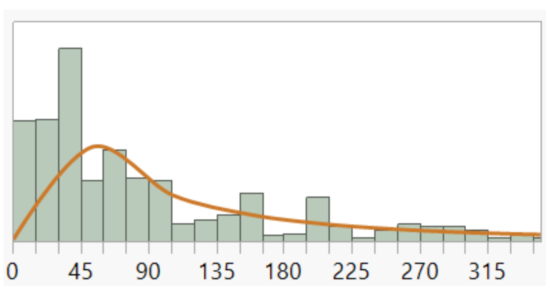
Assessing cost is extremely important to the stakeholder because affordability is a key facet of the FVL program (Martin, 2017). Therefore, the capstone team needed to develop a costing strategy to assess the relative effect of MFOP alternatives on program cost. The capstone team pursued a costing estimate strategy that accounted for the cost to perform a repair (materiel and manpower estimates).

$$MFOP\ Alternative\ Cost = Materiel\ Repair\ Cost + Labor\ Repair\ Cost \tag{2}$$

The ability to calculate the cost to perform a repair was dependent upon linking repair cost data to airframe part failure data. The Logistic Maintenance Institute's (LMI) Maintenance and Availability Data Warehouse (MADW) contains repair cost data. Because MADW uses different unique part identification codes than the part failure data component, cost repair data could not be directly related to component repair data using existing data. Manually correlating unique identification codes for individual components from the component titles was infeasible due to the limited information in the database. Instead, the capstone team linked the cost data to the part failure data at the sub-system level. Grouping the repair data by subsystem required the correlation of 46 subsystems as opposed to 2,189 individual components.

To correlate the two data sets, the team compared the part repair data subsystem nomenclature with the cost data subsystem nomenclature. Tentative equivalent relationships were established for each subsystem within each dataset. For example, the functional group code "32" (Hellfire subsystem) from the part repair data was connected to the "Armament Missile" Tier 1 object from the LMI cost data. Once a logistics management subject matter expert (SME) from FVL confirmed and validated the relationships we created, the link between fault data and cost data was established (Walker, 2021).

Because the capstone team was looking at the subsystem level and not the component level, the team decided to model repair costs using a distribution. Not all repairs performed on the rotary subsystem would cost the same. Using an average repair cost could be potentially misleading because it would not account for higher and lower end cost repairs. Therefore, distributions were required to capture the stochastic nature of component failure costs. Each subsystem was fit to an approximate distribution using JMP statistical software where the parameters could be exported for use in the simulation. Best distribution fit was determined Akaike's Information Criterion (AICc). Figure 4 displays the cost distribution for Functional Group 33, the target acquisition system.



Summary Statistics

Mean	157.51293
Std Dev	332.67232
Std Err Mean	5.3134137
Upper 95% Mean	167.93025
Lower 95% Mean	147.09561
N	3920

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	4.2540078	0.0195797	4.2156228	4.2923927
Shape	σ	1.2258845	0.013845	1.1992415	1.2535289

Figure 4. Target Acquisition System Histogram and Distribution Summary Statistics

Functional Group 33 and every other functional group's repair cost data most closely fit a Lognormal distribution. This distribution fit is significant because it allowed the team to perform cost analysis on the Apache using real cost and repair data. Modeling Apache subsystem repair costs using a Lognormal distribution allowed the capstone team to analyze the cost of MFOP activities more accurately than using repair cost averages.

2.4 Modeling, Simulation, and Design Space Investigation

Using the simulation software, ProModel, the team simulated the flight operations and maintenance of a single AH-64E. The team varied performance parameters for the "Fix & Fly" scenario and collected MFOP metrics for further analysis. The "Fix and Fly" scenario assumes that in the event of a fault (component failure), the maintenance team will complete a limited repair and then will finish the operating period. To quantify the implementation of alternative technologies into the AH-64 MFOP Model, the team varied initial parameters based off the technology impacts matrix (Table 1). Mean Time to Repair (MTTR), Fault Detection/Identification (FD/FI), and Scheduled Maintenance (SM) are input parameters of the ProModel simulation. The capstone team captured the effects of implementing a single technology through a simulation multiplier. Each technology has a proportional impact on the four input parameters as shown in Table 1. The AH-64 MFOP Model returns six MFOP performance metrics which are used to assess alternatives with respect to value and cost. The six-performance metrics are MFOP duration, MFOPS, MR, Achieved Availability, MRP duration, and MRPS. These MFOP performance metrics are the input parameters to the value model created by the capstone team, returning a value score for that MFOP enhancing activity. Quantifying these performance metrics allowed the team to effectively measure and assess MFOP performance and analyze the implementation of various alternative technologies. MFOP duration and MRP duration comprise the two components of an aircraft operation and maintenance cycle (Figure 1) making them important metrics for aircraft performance. Additionally, the respective successes of MFOP and MRP are important metrics because they quantify the reliability of the aircraft during

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planned operation and recovery periods. It is crucial for commanders to have aircraft available for operation and be able to trust the aircraft will successfully complete assigned missions.

2.5 Design of Experiments for Statistical Analysis

The AH-64 MFOP Model takes several minutes to run a single replication. For each run, or replication, the model simulates twelve 100 flight hour cycles to account for the twelve months of operation totaling 12,000 flight hours. The baseline model runs 30 iterations of those twelve cycles for each variation of the input parameters. The large sample size allows the distribution of data from this complex system to approach a normal distribution. Unfortunately, it is not feasible to iterate all combinations possible of alternative technologies through the AH-64 MFOP Model due to time and computing restraints. A recommendation for future work is to use a design of experiments (DOE) to minimize the number of iterations and combinations required while still providing a recommendation to the stakeholder with a desired level of statistical confidence.

3. Conclusion

This technical paper applied the TIES methodology to develop a value model and relative cost model that informs the client on the effect of MFOP enhancing activities for FARA. The capstone team developed a value function to assess alternative technologies with respect to the metrics of MFOP duration, MFOPS, MRP duration, MR, MRPS and Achieved Availability. Using feedback from a stakeholder survey, the capstone team generated weights for the value model to account for stakeholder interests. The stakeholder feedback indicated that MFOPS and MFOP duration are by far the most important metrics to the stakeholders. This finding highlights the fact that the focus group that completed the survey, on average, sees success in the operating period separate from success in the recovery period. The capstone team discovered that repair costs per subsystem follow a lognormal distribution and used the lognormal distributions based on functional code to analyze relative cost during MFOP modelling. After generating the cost and value models, the capstone team identified the technologies from the FirePoint study as the MFOP enhancing activities, to explore as alternatives for this system. Enabling the CFT to understand the impacts of emerging technologies on MFOP would be a significant and interesting compliment to the FirePoint study on operational availability. In future work, the two models developed by the capstone team, in conjunction with simulation data from the AH-64 MFOP Model, shall be used to quantitatively rank MFOP enhancing activities.

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