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Materiel Availability Modeling and Analysis for a Complex Army Weapon System

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SUMMARY & CONCLUSIONS

Materiel availability (A_m) is a new Department of Defense Key Performance Parameter (KPP) implemented through a mandatory Sustainment Metric consisting of an Availability KPP and two supporting Key System Attributes (KSAs), materiel reliability and ownership cost. Sandia National Laboratories (Sandia), in conjunction with several US Army organizations, developed the analytical foundation, assumptions, and brigade-level modeling approach to support lifecycle, fleet-wide A_m modeling and analysis of a complex Army weapon system. Like operational availability (A_o), A_m is dependent on reliability, but A_m is also affected by other factors that are not part of A_o. The largest factors that influence A_m are technology insertion and reset downtimes. A_m is a different metric from A_o. Whereas A_o is an operational measure, A_m is more of a programmatic measure that covers a much larger timeframe, additional sources of downtime, and additional sources of unscheduled maintenance.

1 INTRODUCTION

Materiel availability is a new Department of Defense KPP implemented through a mandatory Life Cycle Sustainment Metric. The sustainment metric consists of an Availability KPP that includes two availability metrics, the more familiar A_o and the new A_m, and two supporting KSAs, Reliability and Ownership Cost. The intent of the sustainment metric is to provide defense system design, development, and acquisition with more informed decision making across a broader assessment trade space defined by the availability metrics, reliability, and ownership cost. "Establishing and managing the materiel availability metric requires the consideration of all of the sustaining support that the acquisition and logistics professional must provide to sustain the capability being acquired, in addition to the reliability and maintainability characteristics of the system itself." [1].

A_o is defined over a specific set of systems in an organizational structure over a defined mission usually defined in days. A_m, a much broader metric than A_o, is defined to measure the operational readiness of an entire fleet of systems throughout the system lifecycles, from placement into operational service through the planned end of service life [2]. A_m is a measure of the percentage of the total inventory of a system operationally capable (ready for tasking) of performing an assigned mission at a given time, based on materiel condition. For fielded systems, A_m is a calculation of the percentage of the system fleet that is operational. For not-yet-fielded systems, A_m is estimated, usually through modeling and simulation, with the usual availability formulation of uptime divided by total time.

Both A_o and A_m metrics are clearly dependent on system reliability, but availability (essentially a measure of system reliability for repairable systems) includes downtime, which is dependent on sustainment operations and capabilities. Availability analysis involves analysis of the sources and durations of downtimes that occur during the timeframes. A_o includes only the sources of downtime during the specific mission and these sources are usually restricted to only system failures and any unscheduled maintenance performed, along with associated activities, that returns systems to mission operational states. In contrast, analysis and estimation of A_m for new acquisition programs requires determination of all the possible sources and durations of downtimes during the lifecycle timeframes of the fleet of systems.

A_o and A_m are related through system reliability, but their definitions, covered timeframes, and meanings are different. The Sustainment Metric requirement for estimation of these metrics envisions these metrics to be traded against each other and their associated ownership cost, with A_m capturing some downtimes and associated costs that are rarely, if ever, considered in design, development, and acquisition.

The System of Systems Analysis Toolset (SoSAT) simulation was used to model and analyze A_m for the Army weapon system and determine estimates of A_m to be used as requirements. SoSAT is being developed and applied by Sandia for the US Army to model and analyze complex system of systems (SoS) capabilities and performance.

Sandia, in conjunction with several US Army organizations, developed the analytical framework, assumptions, and brigade-level modeling approach to provide A_m modeling and analysis of the Army weapon system. These Army organizations included Program Executive Office Integration (PEO-I), Combined Arms Support Command (CASCOM) Sustainment Center of Excellence (SCoE), Training and Doctrine Command (TRADOC) Maneuver Center of Excellence (MCoE) – Ft. Knox, Army Materiel Systems Analysis Activities (AMSAA), Army Materiel Command (AMC), and Army Test and Evaluation Command (ATEC) Army Evaluation Center (AEC). The Office of the Secretary of Defense (OSD) also participated.

2 MODELING AND ANALYSIS APPROACH

The modeling approach developed to estimate A_m requirements consisted of forming a complete picture of the operations, sustainment, and support of the entire fleet of systems over their lifecycles. This complete operational lifecycle of the fielded systems to the brigade set was modeled in SoSAT. System lifecycles and operations were defined based on the Army Force Generation (ARFORGEN) Model for fielding, training, and deploying systems and soldiers. Collecting data and information to define the assumptions of operations, sustainment, and all occurrences of downtime were significant efforts involving several organizations.

2.1 SoSAT

SoSAT is a set of tools centered on a simulation tool and includes relational databases, input and output interfaces, system reliability models, state modeling, SoS functional dependencies and redundancies, and optimization capabilities. The SoSAT simulation is a multi-system, time-step stochastic simulation capability being developed and applied by Sandia for the US Army. Sandia has integrated reliability, availability, supply chain, and state modeling concepts into SoSAT based on research and applications experience with complex, high-consequence systems.

SoSAT has also been developed to model and analyze complex SoS capabilities and performance. It provides the capability to model individual systems down to spare parts, collections of systems in organizational structures up to Army brigade levels, and multiple brigades operating over time. Missions to be modeled can range from small, high-utilization operational missions to longer-term missions up to peacetime training and lifecycle timeframes. SoSAT models system operational performance and system reliability and maintainability along with the detailed repair, supply, and sustainment operations that support them, including competition for resources. For SoS performance modeling, SoSAT models user-defined functional dependencies and redundancies that comprise SoS-level performance, where system performance can be dependent on the performance of other systems, subsystems, and conditions.

2.2 Lifecycle Definition based on ARFORGEN

System lifecycles and operations were defined based on the ARFORGEN Model, depicted in Figure 1 [3]. "ARFORGEN defines the structured progression of increased unit readiness over time." [3]. These units are prepared for deployment as they proceed through the Reset and Train, Ready, and Available force pools.

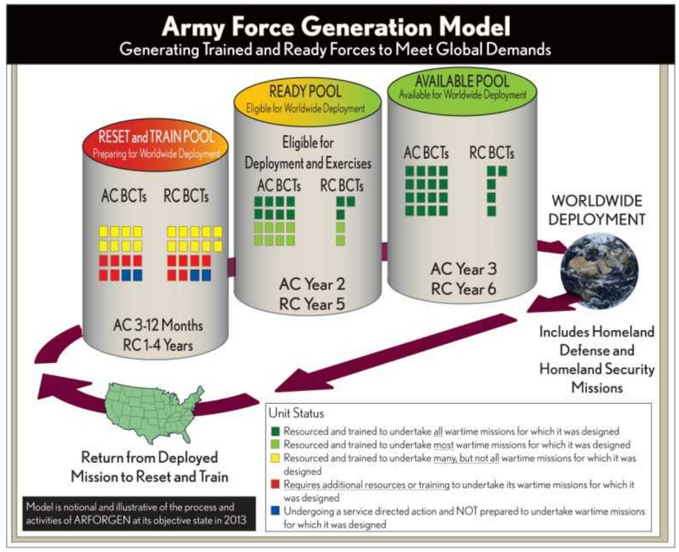

Figure 1. Army Force Generation Model Overview

Units in the Reset and Train redeploy from operations, receive and stabilize personnel, reset equipment, and conduct individual and collective training. The Reset and Train phase culminates in a brigade-level collective training event. The Available force pool are in their planned deployment windows and are fully trained, equipped, and resourced to meet operational requirements. These requirements and operations were used to determine the system utilizations over their lifecycles comprised of these ARFORGEN years. For A_m modeling, the weapon system's Operational Mode Summary / Mission Profile (OMS/MP) provided an operational tempo (OPTEMPO) for the vehicles operating during the Reset and Train period (ARFORGEN year 1), the Ready period (ARFORGEN year 2), and the Available period (ARFORGEN year 3), which was assumed to be a deployment.

3 LIFECYCLE ASSUMPTIONS FOR SYSTEM A_m MODELING

To define system lifecycles based on ARFORGEN, a representative system fielding schedule was developed to determine placement into service that begins the lifecycle. Systems were assumed to be deployed to a set of brigades over time, beginning their conduct of operations according to the ARFORGEN cycle with peacetime training (ARFORGEN years 1 and 2) and then operations during wartime deployments (ARFORGEN year 3). Once lifecycle durations and operations were determined, the impacts of system aging were incorporated into the model. Major sources of downtime were then defined and incorporated into the model, including reset after deployment, technology insertion periods, unscheduled maintenance, scheduled maintenance, and combat damage repair. In addition to determining A_m estimates, the model was used to perform A_m sensitivity analyses on a variety of factors.

System lifecycles were further defined based on the ARFORGEN Model with the following assumptions:

- Each brigade repeats the 3-year cycle 7 consecutive times (defining a 21-year lifecycle for the systems).
- Every 3rd year of the ARFORGEN cycle is a wartime deployment, representing a strenuous operational cycle.
- Brigade OPTEMPOs are aligned with the system's OMS/MP for 2 years of peacetime sustainment training periods and a 1-year wartime deployment.
- Brigades are fully equipped per their Table Of Organization And Equipment (TOE) and at 100% readiness at start of deployment.
- Weapon systems used for institutional training (IT) align their annual OPTEMPO with the 2nd ARFORGEN year training OPTEMPO depicted in the system OMS/MP.
- System floats are deployed with their respective brigade and their OPTEMPOs are aligned with the system OMS/MP.

3.1 Representative Fielding Schedule

Since A_m is required to cover the entire life of the fleet, a representative fielding schedule was developed that integrated staggered fielding to 17 brigades, incorporated the ARFORGEN Model, accounted for reset periods after deployment, allowed for technology insertion, and incorporated a definitive 21-year end of life for each system. The 21-year lifecycle was used to be close to the usual 20-year lifecycles used in lifecycle costing and yet incorporate the ARFORGEN 3-year cycles. This life cycle schedule accounted for the entire fleet, including Institutional Training systems and floats even though the training systems are not part of the brigade. The following assumptions further defined the fielding schedule and life cycle parameters:

- The weapon systems are fielded to equip two brigades per year along with their associated floats and institutional training systems.
- The fleet of systems spans 29 years from first fielded brigades through end of life for the systems fielded to the last brigade.
- Reset periods occur during the first six months of the Reset and Train period following a deployment.
- Technology insertion occurs once during the system's lifecycle in the middle of the fleet's 29 year span.

Figure 2 depicts this representative fielding schedule and fleet life cycle, with blue blocks indicating operational periods, orange blocks corresponding to reset periods, and yellow blocks identifying potential technology insertion periods over the 29-year fleet life.

3.2 ARFORGEN Cycles

Figure 3 shows a plot of instantaneous A_m over the initial 3-year ARFORGEN cycle and the 1st year of the next 3-year cycle, comprising the first 4 years of the 21-year lifecycle (note that year 1 is different than year 4 since there is no reset period at initial fielding; year 4 and every 3rd year thereafter is ARFORGEN year 1 with reset). Also shown in the chart in Figure 3 are periods for scheduled maintenance, a recovery period for preparation for deployment, and the reset period following the deployment year.

3.3 Deployment Year

The deployment year OPTEMPO for the weapon systems was derived from the system OMS/MP that defines a notional 180-day campaign comprised of a Major Combat Operation (MCO), an Irregular Warfare (IW) Operation, and a Peacekeeping/Stability Operation (PO). Sustainment/recovery periods were interspersed between major operations and the PO mission was extended by a day to create a 182.5-day scenario, which is repeated once to form the year-long deployment scenario. OPTEMPOs for other vehicles within the brigade were developed similarly or by using OPTEMPOs depicted in the weapon system OMS/MP for like systems.

3.4 Reset Period

The SoSAT model incorporates reset of the brigade systems after a deployment. Reset consists of major maintenance operations to return deployed systems to operational standards and an increase in reliability. For this analysis, it was assumed that reset would occur during the first 6 months following the deployment year. Only systems that were deployed (including floats) go through reset, thus the Institutional Training systems do not go through reset during their 21-year life since these systems do not deploy. Systems undergoing reset experience a delay for transportation time (from theater to the reset site/facility), with the duration of reset operations represented by a uniform time distribution.

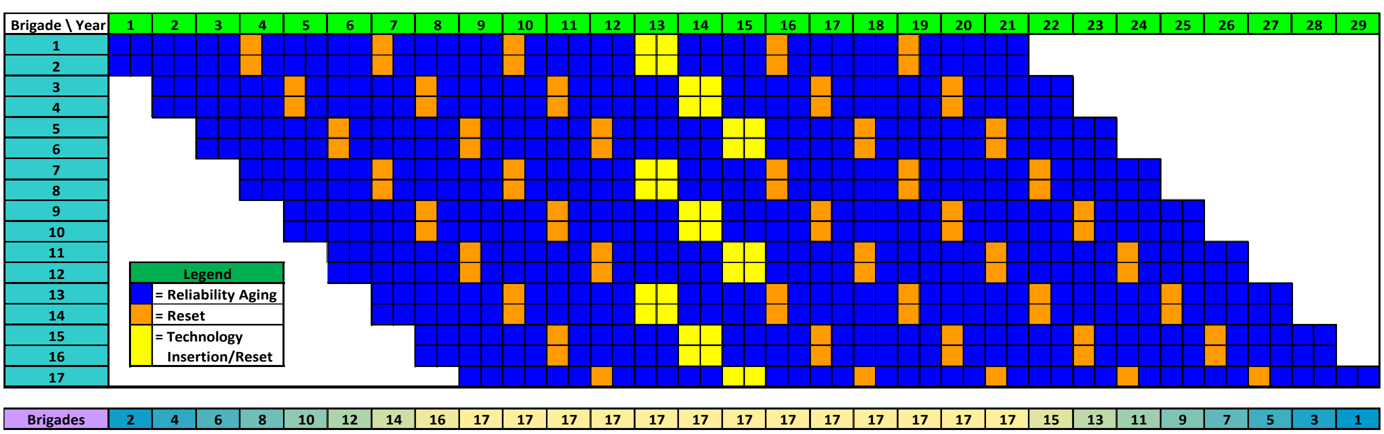

Figure 2. System Fielding Schedule and Lifecycles

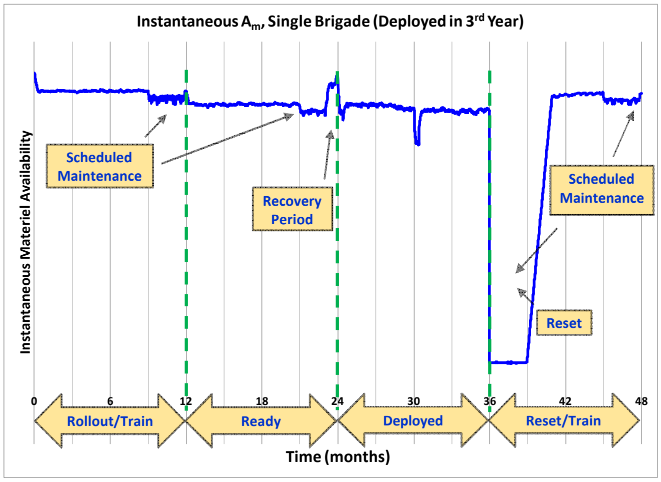

Figure 3. Instantaneous System A_m in a Single Brigade (First Four Years of Lifecycle)

3.5 Technology Insertion Period

To integrate technology insertion opportunities and model the corresponding reliability improvements into the A_m analysis, it was assumed that one technology insertion period would occur for the fleet of systems. This period was assumed to occur during the middle years of the 29-year fleet lifecycle period (years 13-15). All integrated weapon systems, including floats and Institutional Training systems, would undergo technology insertion over that 3-year period. The technology insertions would take place during those years that reset would have normally occurred, although the technology insertion was assumed to require more time than reset, as shown in Figure 2. Institutional Training systems would complete tech insertion over the same 3-year period. The weapon systems undergoing technology insertion experience the same delay for transportation time from theater to the reset site/facility, with the duration of reset and technology insertion represented by a time distribution.

3.6 Impacts of Aging

To incorporate the impacts of aging on the system fleet, reliability degradations were assumed and modeled for each year of operation based on the OPTEMPO expected for that particular year. Thus, reliability degradations, reset, and technology insertion produce different reliability profiles across the systems over the different brigades. Based on the representative fielding schedule shown in Figure 2, there are 3 distinct reliability profiles, for brigades 1-6, 7-12, and 13-17. Institutional Training systems are also impacted by aging, but on a separate schedule due to their lower OPTEMPO and lack of reset. The detailed reliability aging assumptions were based on an aging study [4] that analyzed data from the field.

4 OTHER MODELING ASSUMPTIONS

Additional details of the weapon system characteristics that impact downtime incurred for unscheduled maintenance, scheduled maintenance, combat damage repair, and waiting for spare parts within the constraints of the brigade organizational structure were also defined. Each of these specific areas were defined with data that was derived from system requirements, surrogated data from real systems, or provided by experts from the Army organizations involved.

4.1 Unscheduled Maintenance

Unscheduled maintenance occurs when the weapon system experiences a reliability failure or durability failure that requires maintenance to remedy the failure and bring the system back to an operational status. For the purposes of this A_m analysis, only System Aborts (SAs) and Essential Function Failures (EFFs) resulted in unscheduled maintenance. SAs were the driver for unscheduled maintenance during MCO and IW Operations for the wartime deployment period (ARFORGEN Year 3), and EFFs were the driver for unscheduled maintenance during the PO of the wartime deployment period and during peacetime sustainment training (ARFORGEN Years 1 and 2). It should be noted that Non-Essential Function Failures (NEFFs) were not considered drivers for availability. These failures are often deferred until scheduled maintenance periods or repaired in conjunction with SA or EFF failures provided parts were available.

The weapon system reliability was defined by threshold and objective requirements in Mean Miles Between System Abort (MMBSA) and Mean Miles Between Essential Function Failure (MMBEFF). The brigade and float system reliablities were assumed to degrade due to aging by specific percentages in each of the ARFORGEN years, as discussed previuosly.

Unscheduled maintenance was also modeled to include maintainability assumptions for time to repair, percent crew repairable, and maximum time to repair. These assumptions were derived from the system requirements.

4.2 Scheduled Maintenance

When the system exceeds a scheduled maintenance trigger, described by miles of operation, clock hours of usage, or calendar time, scheduled maintenance is conducted. It provides a systematic means of inspection, detection, and correction of incipient failures before they occur or develop into major problems. Scheduled maintenance also provides an opportunity to repair NEFFs that have been deferred. The scheduled maintenance assumptions were derived from the system requirements. Scheduled maintenance was then modeled according to the operational usage that determined when the actions were required and with assumed downtime.

4.3 Combat Damage Repair

Repair of combat damaged systems is a unique capability that differs significantly from unscheduled maintenance actions in terms of repair time, resources required, and what echelon will complete the repair action. Therefore separate and distinct attributes were developed to define combat damage repair for modeling purposes. These include the following elements:

- Combat damage only occurs during deployment.
- Combat damage renders the systems incapable of continuing in service and requires immediate repair and/or recovery.

- Catastrophic (non-repairable) combat damage to systems is not modeled since it is assumed that those vehicles would be replaced through production line vehicle increases (for A_m purposes, those systems would be considered not part of the fleet anymore).
- Repairable combat damage during deployment is assessed as an annual percentage of those requiring repair outside the brigade with a considerable downtime (includes transportation, maintenance, and spares wait time).

4.4 Spare Parts Delay Times

Assumptions were made for modeling spare parts fill rates and associated delay times for spares at various locations within the brigade and at Echelons Above Brigade (EAB) for different operations within the Full Spectrum of Operations while deployed. Part fill rates and delays were specified for reliability failures of the weapon systems and the other brigade systems during the MCO, IW, and PO missions as well as for weapon system combat damage repair.

For peacetime training operations conducted during ARFORGEN Years 1 & 2, a different set of delay times was developed from repair cycle time (RCT) data on current systems. The RCTs include delay times for maintenance, spares, and recovery consolidated into a single value.

5 A_m MODELING AND ANALYSIS RESULTS

The results of conducting SoSAT model runs to determine system A_m are presented in two aggregated areas: a single brigade-level system result covering 21 years and a fleet wide system result over the 29-year fleet span.

5.1 Single Brigade-Level System Results

Yearly average A_m results for a single brigade's weapon systems for each of the 21 years in the lifecycle are shown in Figure 4. The availability varies by year due to varying OPTEMPOs, impacts of reset events after deployment, impacts of aging, and the impacts of technology insertion. The resultant lifecycle average A_m is shown in the figure as the purple horizontal line. Also shown in the chart are A_o values for MCOs in the deployment years and the number of EFFs occurring across the brigade systems by year. The number of EFFs provides an indication of ownership costs, with replenishment spares being a significant part of costs, showing the potential tradeoffs of A_m with A_o and costs.

5.2 Fleet-Wide System A_m Results

Fleet-wide system yearly average A_m results for each year of the 29 years of the system fleet lifecycles for the 17 brigades are shown in Figure 5. The A_m varies by year due to the staggered fielding schedule, varying OPTEMPOs, reset events after deployment, fleet aging, and technology insertion. The resultant threshold global fleet average A_m is shown in the figure as the purple horizontal line. Note that the A_m metric is a global average value calculated over the fleet life over 29 years, and is not the average of the yearly averages. Each year has a distinct A_m average value that varies around the fleet average A_m based on the factors that impact fleet wide

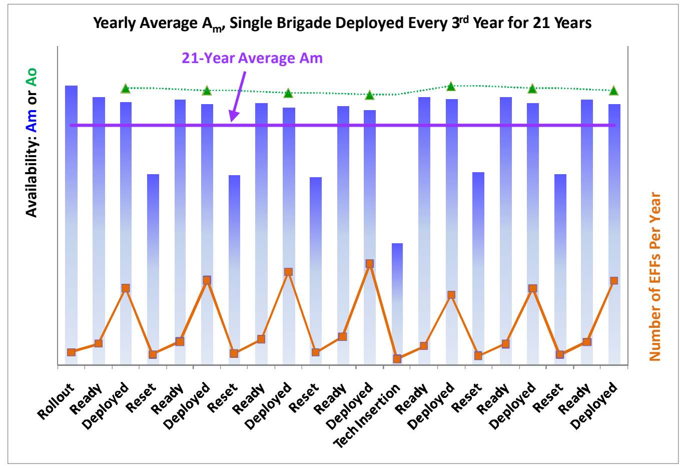

Figure 4. Average Weapon System A_m for a Single Brigade over a 21-Year Lifecycle

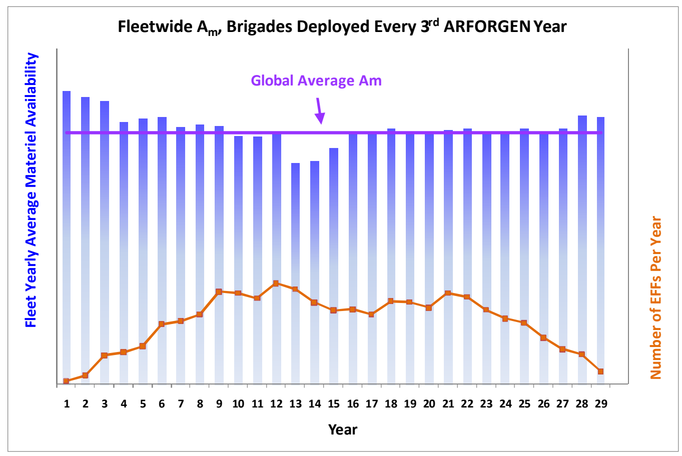

Figure 5. Weapon System Fleet Average A_m for 29-Year Fleet Lifespan

availability. Also shown in the chart are the number of EFFs occurring across the fleet year by year.

5.3 Follow-On Analyses

Follow-on analyses were performed for threshold and objective requirement values to investigate the relationships and sensitivities of A_m to several factors. The following results were determined through these analyses:

- Factors with large impacts on system A_m:
  - Reliability
  - Reset and technology insertion downtimes
- Factors with little impact on system A_m:
  - Combat damage rates
  - System fielding schedules
  - Extended deployment (to 15 months)
  - Lifecycle extension (from 21 to 30 years)
  - Small reliability improvements due to FRACAS
- Impacts of reset and technology insertion reliability improvements on A_m are largely offset by downtimes from the reset and technology insertion activities
  - Number of EFFs, A_o affected more significantly
- Peacetime-only assessment (no deployment) conducted
  - Aligns with life cycle cost methodology

Additional analyses were also performed to support the weapon system analysis of alternatives. These results are summarized in the chart shown in Figure 6.

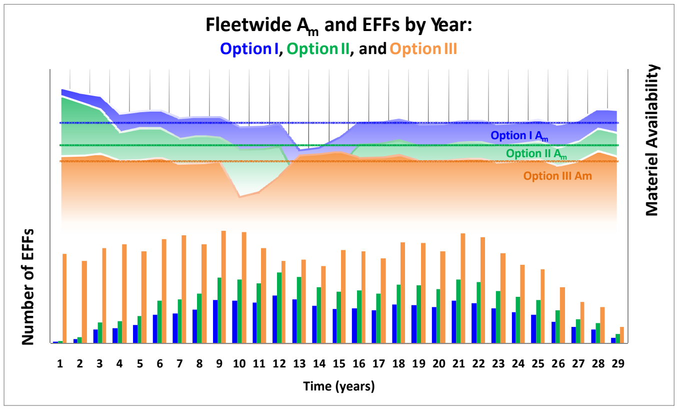

Figure 6. Weapon System Analysis of Alternatives Results

6 CONCLUSIONS

Like A_o, A_m is dependent on reliability, but A_m is also affected by other factors that are not part of A_o. The largest factors that influence A_m are the technology insertion and reset downtimes. A_m is a different metric than A_o. Whereas A_o is an operational measure, A_m is more of a programmatic measure that covers a much larger timeframe and additional sources of downtime. With the expanded timeframes and sources of downtime iin comparison to usual availability analysis, A_m modeling requires a significant effort to define modeling assumptions and to perform the modeling that requires larger-scale models and longer run times.

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REFERENCES

1. R. T. Fowler, S. P. Kilroy, "Life Cycle Metrics and OSD Oversight: Discipline With Flexibility," *ITEA Journal*, vol. 29, (Sept.) 2008, pp 263-266.
2. *Department of Defense Reliability, Availability, Maintainability, and Cost Rationale Report Manual*, Washington, DC, Office of the Secretary of Defense, (June) 2009.
3. "Addendum H: Army Force Generation," *2007 U.S. Army Posture Statement,* U.S. Army, accessed (July) 2010, <http://www.army.mil/aps/07/addendum/h.html>.
4. E. Peltz, L. Colabella, B. Williams, and P. M. Boren, *The Effects of Equipment Age on Mission-Critical Failure Rates: A study of M1 Tanks*, RAND Corporation, 2004.

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