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AN ANALYSIS ON THE EFFECTS OF ADDITIVE MANUFACTURING (AM) ON F/A-18E/F READINESS

by

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June 2022

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This research paper focuses on the Boeing F/A-18E and the F/A-18F Super Hornet aviation depot level repairable (AVDLR) parts process and the potential effects of additive manufacturing (AM) on that process. The motivation for study was spurred by recent reports indicating that the F/A-18E/F is experiencing decreased operational readiness due to increases in maintenance-related impacts related to parts availability, long lead times, and increased parts failure frequency. This study aimed to determine the requirements for interjecting AM into the Intermediate level repair process in order to make a significant impact on F/A-18E/F depot-level repairable part lead times. More specifically, this research analyzes the potential impact of various AM production levels on overall lead times. Facilitation of this research project was accomplished through mathematical modeling and by conducting simulations based on various assumptions and probability distributions. Eight simulations were conducted, each with different AM production time assumptions. Resultant outputs reflected 19 different scenarios simulating 0%–90% production of AM at the Intermediate Maintenance level. Results indicate that AM has the potential to decrease overall expected lead time averages if AM production can be kept to less than approximately 30 days.

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This research paper focuses on the Boeing F/A-18E and the F/A-18F Super Hornet aviation depot level repairable (AVDLR) parts process and the potential effects of additive manufacturing (AM) on that process. The motivation for study was spurred by recent reports indicating that the F/A-18E/F is experiencing decreased operational readiness due to increases in maintenance-related impacts related to parts availability, long lead times, and increased parts failure frequency. This study aimed to determine the requirements for interjecting AM into the Intermediate level repair process in order to make a significant impact on F/A-18E/F depot-level repairable part lead times. More specifically, this research analyzes the potential impact of various AM production levels on overall lead times. Facilitation of this research project was accomplished through mathematical modeling and by conducting simulations based on various assumptions and probability distributions. Eight simulations were conducted, each with different AM production time assumptions. Resultant outputs reflected 19 different scenarios simulating 0%–90% production of AM at the Intermediate Maintenance level. Results indicate that AM has the potential to decrease overall expected lead time averages if AM production can be kept to less than approximately 30 days.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIMD	Aviation Intermediate Maintenance Department
AM	Additive Manufacturing
ASD	Aviation Supply Depot
ASD	Aviation Support Detachment
ASD (Sustainment)	Assistant Secretary of Defense for Sustainment
AVDLR	Aviation Depot Level Repairable
AWP	Awaiting Parts
BCM	Beyond Capable Maintenance
BUNO	Bureau Number
CCS	Component Control Section
D-Level	Depot Level
DLR	Depot-Level Repairable
DMLS	Direct Metal Laser Sintering
FLR	Field-Level Repairable
FRC	Fleet Readiness Center
GE	General Electric
ICP	Inventory Control Point
I-Level	Intermediate Level
IMA	Intermediate Maintenance Activities
LRCA	Local Repair Cycle Assets
MAF	Maintenance Action Form
MDU	Material Delivery Unit
NAMP	Naval Aviation Maintenance Program
NAS	Naval Air Station
NC	Not Carried
NIIN	National Item Identification Number
NIS	Not in Stock
NMC	Not Mission Capable
NMCM	Not Mission Capable Maintenance
NMCS	Not Mission Capable Supply

O-Level	Operational Level
PBL	Performance-Based Logistics
PEB	Pre-expended Bin
PMU	Program Management Unit
RCU	Requisition Control Unit
RFI	Ready for Issue
SLM	Selective Laser Melting
SM&R	Source Maintenance and Recoverability
SRA	Shop Repairable Assembly
SRS	Supply Response Section
WRA	Weapon Repairable Assembly

I. INTRODUCTION

A. PURPOSE

F/A-18E/Fs are increasingly suffering readiness shortcomings and shortages, a growing problem that is lacking a viable solution (Pike, 2018). The lack of mission capable F/A-18E/Fs could potentially grow from a readiness issue to a national security issue, due to the lack of aircraft to carry out their designed mission. This study aims to determine the baseline requirements for interjecting additive manufacturing (AM) into the Intermediate level repair process in order to make a significant impact on F/A-18E/F depot-level repairable part lead times. More specifically, this research analyzes the potential impact of various AM production levels on overall lead times.

B. BACKGROUND

The Boeing F/A-18E and the F/A-18F Super Hornets are the U.S. Navy's primary fighter and attack jet aircraft currently in service. As the Navy's premier multi-role jet, the fleet of roughly 603 aircraft has been consistently utilized ever since their first production in 1995. While the F/A-18E/F is considered to be relatively young compared to contemporary aircraft such as the McDonnell Douglas F-15 Eagle, recent reports indicate that this airframe is experiencing decreased operational readiness due to increases in maintenance related impacts (Pike, 2018). These maintenance impacts are largely caused by a variety of underlying issues such as parts availability, long lead times, and increased parts failure frequency (Ziezulewicz, 2019). With the rapid development of AM technologies, the Navy (and the aviation industry at large) is persistently evaluating the applicability of AM (Wilson, 2020). AM is still in its infancy in regard to implementation in the U.S. Navy, but the potential for 3D printing parts is ever present (Wilson, 2021). To combat the readiness issues for the F/A-18E/F, the U.S. Navy needs to continue exploring the capabilities of AM, and ultimately, determine if AM's application to aviation depot level repairable (AVDLR) repair would sufficiently improve readiness.

The F/A-18E/F has been operating for years and is continuously being extended past its originally designed service life expectancy thresholds (Pike, 2018). Contributing factors can be attributed to lack of available parts from obsolescence, long lead times for replacement components, and an increase in parts failure frequency. Subsequently, F/A-18E/F squadrons are resorting to cannibalization maintenance techniques to keep their aircraft flying (Ziezulewicz, 2019). This is only a temporary solution as it causes the other aircraft to consistently become not mission capable (NMC). If an alternative solution is not found for these issues, then readiness is going to continue to be negatively impacted, resulting in more NMC aircraft. This, in turn, creates a domino effect of far-reaching and potentially damaging impacts. For example, a decrease in operationally available Super Hornets would reasonably affect the ability for pilots to maintain their qualifications or conduct mission critical sorties, thus compromising the nation's security abilities. While the U.S. Navy has already begun its implementation of AM technologies, knowledge of AM's capabilities and applications are still considered to be in its infancy (Wilson, 2021). AM could potentially be a viable solution to the readiness issues currently facing the F/A-18E/F based on research that has already been conducted (Kenney, 2013). Further research needs to be conducted on the benefits of producing an F/A-18E/F AVDLR. The hope is that producing a component in-house via 3D printing will not only be more cost efficient but also more expedient than current supply processes. This anecdotal hope speaks to a major knowledge gap with regards to AM's effects on part procurement lead times. The goal of this research paper is to apply the solutions from our findings to determine if readiness would be improved.

C. RESEARCH QUESTION

Will 3D printing F/A-18E/F Depot Level Repairable (DLR) components improve lead time's and, in-turn, improve readiness within the F/A-18E/F fleet? How much of the DLR components need to be 3D printed to make an appreciable difference on lead times? If AM turns out to be a viable solution, not only will this singularly help the F/A-18E/F platform but could also potentially improve readiness in other similar weapons systems as well.

D. EXPECTED BENEFITS OF STUDY

Through this study we expect to find that interjecting 3D printing at the intermediate level (I-level) for maintenance will improve the overall lead time of DLRs. The results of this study could then be used to derive an associated value of improved lead time compared to the cost of implementing 3D printing. Improvements in operational readiness are also expected since non-operational aircraft will not be waiting as long for parts. If AM turns out to be a viable solution, not only will this improve the F/A-18E/F readiness, but it could also improve readiness in other weapon systems.

E. LIMITATIONS

The most impactful limitation overall are the effects of the COVID-19 pandemic to industry and the supply chain. The data set for our analysis was drawn from 2021 to the first quarter of 2022. It is possible there are underlying effects to lead times which will improve as industry and transportation return to pre-pandemic operations. A second limitation of our study is we only used a small portion of data compared to the number of years and maintenance facilities who repair DLRs. A third limitation is our use of industrial standard lead times for 3D printing. We did not have data for the length of time required for the I-level to print different types of parts. A fourth limitation of our study is whether or not the DLR can actually be repaired with a 3D printed part. The inability for repair could be a number of factors including engineering requirements, composition, size, or complexity.

Despite these limitations, our study is useful because it encompasses a methodology that can be utilized for future F/A-18E/F cost-benefit analyses as well as other weapon systems in which AM has the high potential of being applied.

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II. LITERATURE REVIEW

This review provides an introduction to sustainment of the U.S. Navy F/A-18E/F aircraft, AM/3D printing techniques, the component repair process, and the component order and turn-in process. Next, this study examines the Government Accountability Office (GAO) specific to the F/A-18E/F aircraft, detailing mission capability rates and sustainment issues. Next, the review delves into 3D printing capabilities, benefits, limitations, materials, and settings. Additionally, the Naval Aviation Maintenance Program (NAMP) is reviewed in detail, specifically with maintenance and supply capabilities.

A. F/A-18E/F SUSTAINMENT

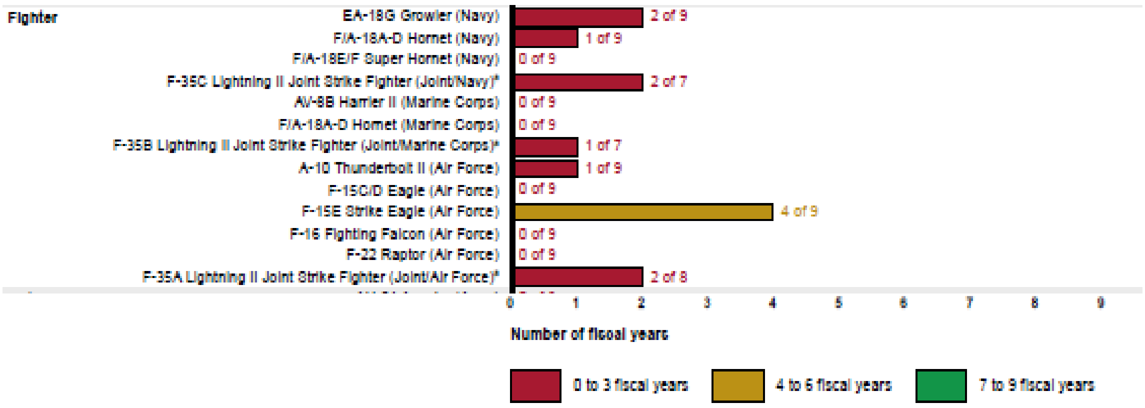
The sustainment of aircraft requires many roles and responsibilities across a variety of DOD offices. These roles and responsibilities are so important the Under Secretary of Defense for Acquisition and Sustainment (USD [A&S]) is charged with it. The USD(A&S) will then advise the Secretary of Defense on any matters related to acquisition and sustainment (Maurer, 2020, p. 5). Maurer went on to say that the USD(A&S) establishes policies for logistics, maintenance, and sustainment support.

> The Assistant Secretary of Defense for Sustainment (ASD [Sustainment]) serves as the principal advisor to the USD (A&S) on logistics and materiel readiness within DOD. Specifically, the ASD (Sustainment) (1) establishes DOD policies and procedures for logistics, maintenance, materiel readiness, strategic mobility, and sustainment support; (2) provides related guidance to the Secretaries of the military departments; and (3) monitors and reviews programs associated with these areas, among other duties and responsibilities. (Maurer, 2020, p. 5)

Specifically for the Navy, there is the Naval Air Systems Command, which provides life-cycle support for its aircraft, weapons, and systems. Life-cycle support includes the very beginning of research and design following into development and continuing all the way to the end with in-service engineering and logistics support. Along with this support, Maurer (2020) described three metrics to monitor readiness, which are used in the GAO report and common across the military branches:

1. **Mission capable rate:** The percentage of total time when an aircraft can fly and perform at least one mission.
2. **Not mission capable maintenance (NMCM) rate:** The percentage of total time when an aircraft is not capable of performing any of its assigned missions because of maintenance.
3. **Not mission capable supply (NMCS) rate:** The percentage of total time when an aircraft is not capable of performing any of its assigned missions because of the lack of a repair part. (Maurer, 2020)

The troubles facing the F/A-18E/F are not just correlated to a single platform. According to the Government Accountability Office (GAO), their findings discovered that three of 46 types of aircraft met the mission capable goals between 2011 and 2019. Of the 43 remaining types of aircraft, 24 of them never met the mission capable goals across the given time frame, with the F/A-18E/F being one of them. Of the 13 fighter aircraft looked at across the Navy, Marine Corps, and Air Force, there were six that did not meet any mission capable goals, three that met one, three that met two, and one that met four. These metrics are reflected in Figure 1.[1]



Source: GAO analysis of Army, Navy, and Air Force data. | GAO-21-101SP

Figure 1. Annual Mission Capable Goals, Fiscal Years 2011–2019. Source: Maurer (2020).

The chart excerpt in Figure 2 shows the causes of some aircraft plagued by sustainment challenges. Figure 2 breaks the sustainment challenges into three categories:

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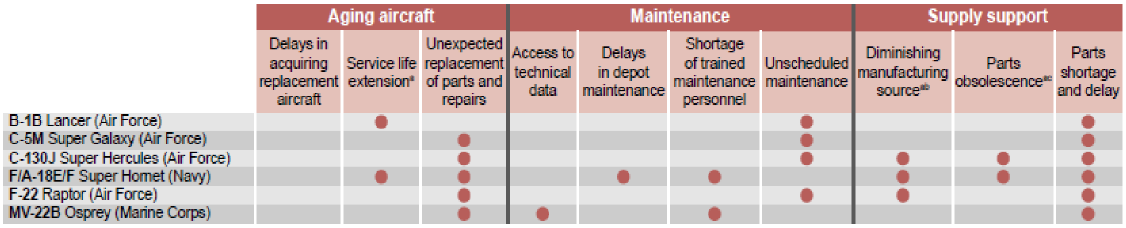
[1] The full chart of all 46 aircraft can be found in Maurer (2020, p. 2).

aging aircraft, maintenance, and supply support. Each of those main categories has three, four, and three subcategories respectively. The colored dot corresponds to an aircraft which has an issue within the given category. As shown, aging aircraft, maintenance challenges, and supply issues all contribute to declining mission capable rates. Currently the F/A-18E/F are affected by seven of the 10 categories presented. These sustainment challenges are also reflected through increased costs. According to Maurer, 20 aircraft involved in their review had increased operation and support (O&S) costs. “The total O&S cost for the F/A-18E/F Super Hornet (Navy) increased by $1.13 billion—from $2.16 billion to $3.29 billion “ (Maurer, 2020, p. 16). This increase occurred between 2011 and 2018. According to program officials these increases were “from continuing systems improvements, the results of sustained high flight hours, and to address extensive maintenance needs associated with extending the service life of the aircraft, among other reasons” (Maurer, 2020, p. 16). The chart excerpt in Figure 3 displays the life cycle of the F/A-18E/F. The planned sunset year of 2045 only adds to the sustainment challenges due to the prolonged life cycle.

Sustainment Challenges Affecting Some of the Selected Department of Defense Aircraft



	Aging aircraft			Maintenance				Supply support		
	Delays in acquiring replacement aircraft	Service life extension[a]	Unexpected replacement of parts and repairs	Access to technical data	Delays in depot maintenance	Shortage of trained maintenance personnel	Unscheduled maintenance	Diminishing manufacturing source[a,b]	Parts obsolescence[a,c]	Parts shortage and delay
B-1B Lancer (Air Force)		●					●			●
C-5M Super Galaxy (Air Force)			●				●			●
C-130J Super Hercules (Air Force)			●				●	●	●	●
F/A-18E/F Super Hornet (Navy)		●	●		●	●		●	●	●
F-22 Raptor (Air Force)			●				●	●		●
MV-22B Osprey (Marine Corps)			●	●		●				●

Source: GAO analysis of Army, Navy, and Air Force information. | GAO-21-101SP

[a] A service life extension refers to a modification to extend the service life of an aircraft beyond what was planned.
[b] Diminishing manufacturing sources refers to a loss or impending loss of manufacturers or suppliers of items.
[c] Obsolescence refers to a lack of availability of a part due to its lack of usefulness or its no longer being current or available for production.

Figure 2. Sustainment Challenges Affecting DOD Aircraft. Source: Maurer (2020).

Source: GAO analysis of Navy data. | GAO-21-101SP

Figure 3. F/A-18E/F Life Cycle Overview. Source: Maurer (2020).

Through the GAO report, the F/A-18E/F has some readiness shortcomings and challenges to overcome. First, the original life of the F/A-18E/F was supposed to be 6,000 hours, but now that has been extended to 10,000 (Maurer, 2020, p. 123). Second, planned maintenance occurs every 72 months. The GOA report does not specify why this time period is a challenge. One could conclude if the maintenance period is too far apart then aircraft could experience more failures between maintenance. If the maintenance period is closer then more aircraft will be needed to maintain the number available to fly. Third, the secretary of defense requires an 80% mission capable goal. This goal is far from being reached since the report states the aircraft is below 50% for a mission capable rate. Fourth, NMCM and NMCS continue to rise because of budget sequestration and funding shortages. Fifth, increasing aircraft inventory is putting more pressure on the maintenance community and manufacturer support activity. Sixth, maintenance costs are increasing with the increase in flight hours. Finally, life-limited components will have to be replaced at 6,000 hours to accommodate the increased life cycle (Maurer, 2020). All of the challenges seem to revolve around an aspect of maintenance. Any improvement one can make in maintenance has the chance to improve multiple challenges.

B. 3D PRINTING

The capabilities of 3D printing have come a long way over the past decade. 3D printing as a form of AM differs from traditional manufacturing in that “Additive manufacturing builds up 3D objects by depositing and fusing 2D layers of material” (Hubs, n.d.-b). Modern 3D printing capabilities have become faster and more cost-effective as the technology has improved.

The strength of 3D printing lies in which parts can be produced in various geometries. This allows flexibility in how the part can be produced. Traditional manufacturing consists of subtractive manufacturing and formative manufacturing. Subtractive manufacturing produces items by removing material from a solid block of material (machining), and formative manufacturing produces a part using a mold, therefore resulting in high set-up costs (Hubs, n.d.-b).

1. 3D Printer Benefits

The potential benefits of 3D printing are very "low start-up costs, quick turnaround, large range of available materials, design freedom at no extra cost, [and] each part can be customized" (Hubs, n.d.-b). In some instances, the low start-up costs are based on the inexpensive cost of the required materials. The quick turnaround is important for potentially producing a high-priority part that has a long lead time that is needed quickly to get an F/A-18E/F operational. F/A-18E/F parts are made up of a wide array of different materials. Having a long range of available material is important for flexibility of being able to produce the required part. Design freedom does not necessarily apply since following the original design of the part is crucial to maintaining part integrity.

General Electric (GE) Additive and GE Aviation have applied these AM advantages. A conventionally made power door opening system bracket was replaced with an additively built bracket on "GE Aviation's GEnx-2B commercial airline engines that power the Boeing 747–8" ("GE Aviation," 2018). The initial Power Door Opening System brackets for the "GEnx-2B engines were [made] from a solid block of metal" and milled ("GE Aviation," 2018). Around half of the material was squandered as a result of this method. "GE Aviation" (2018) details the new techniques that were implemented and the resulting benefits:

> Now using direct metal laser melting (DMLM) additive technology to manufacture the new brackets, waste has been reduced by as much as 90 percent. GE Aviation has also improved the design to reduce the bracket's weight by 10 percent. The decision to mass produce using a cobalt-chrome

> alloy over a traditional nickel-based superalloy has enabled a faster build. To make this approach as efficient as possible, four brackets will be printed at the same time. Using a bespoke, interlocking design to house all four brackets on a single build plate, the Concept Laser M2 cusing machine's pair of lasers can print an aircraft's worth of brackets in one build, before post-processing and inspection. ("GE Aviation," 2018)

This design change has been approved by the FAA according to 'GE Aviation," 2018 and is a potential first step in many more FAA approved parts for a major commercial aircraft. An approval from the FAA for a successfully 3D printed part is a positive step in the potential of AM parts for aircraft that fall under the Department of Defense, being that DOD parts would have to be approved by a government entity as well. Moreover, the speedier build time that resulted in the capability of printing up to four brackets at the same time, could potentially carry over to the F/A-18E/F aircraft and result in receiving the part quicker than the status quo.

2. 3D Printer Limitations

3D printing is not without its limitations. "The limitations of 3D printing include limited accuracy and tolerances and lower strength and anisotropic material properties. Also, the parts are less cost-competitive at higher volumes, and 3D printing requires post-processing and support removal" (Hubs, n.d.-b). Given these limitations, the use of 3D printing would be most beneficial to parts that are causing the F/A-18E/F to be grounded due to NMCS status and may have a long lead time or are not readily available. Using a 3D printer for purposes of mass production is not currently cost-efficient.

> One of the biggest limitations of 3D printing is that most parts are inherently anisotropic or not fully dense, meaning they usually lack the material and mechanical properties of parts made via subtractive or formative techniques. Due to fluctuations in cooling or curing conditions, different prints of the same part are also prone to slight variations, which puts limitations on consistency and repeatability. (Hubs, n.d.-b)

Almost all metal 3D printed parts will require some post-processing before they can be used. This raises the overall cost and lengthens the delivery time. Regardless of the technology used, the final product almost always requires a mix of thermal treatments, machining, polishing, and other finishing methods. Support removal may also be required from the 3D printing as not to damage the part. The delays caused by post-processing and the use for support removal could potentially cause 3D printing a part for an F/A-18E/F slower than the status quo.

3. Metal 3D Printing

The number of 3D printing materials has grown over the years and are continuously developing. Most F/A-18E/F parts are made from metals, composites, and ceramics that have potential of being 3D printed (Hubs, n.d.-b). Metal 3D printers, like all other 3D printing technologies, create items by layering material built on a three-dimensional digital model (Hubs, n.d.-a). Metal materials for metal 3D printing are continuously increasing in quantity. The following alloys can be used to produce parts: "stainless steels, tool steels, titanium alloys, aluminum alloys, nickel-based superalloys, cobalt-chrome alloys, copper-based alloys, precious metals, and exotic metals such as palladium and tantalum (Hubs, n.d.-b)." All these parts are produced via various printing technologies and methods.

The development of Metal 3D printing can be traced back to many decades ago. Direct Metal Laser Sintering (DMLS) was the first patent for metal 3D printing and was filed by a company in Germany called EOS in the 1990s (3D Printing, 2019). New metal printing capabilities and technologies have been developed since then, and have warranted their own patents as well (3D Printing, 2019).

The procedures that each metal 3D printer takes to create a part differ substantially depending on the technology (Hubs, n.d.). Each metal 3D printer will for the most part drop into one of these six categories: "Powder Bed Fusion, Binder Jetting, Metal Material Extrusion, Direct Energy Deposition, and Ultrasonic Additive Manufacturing" (Hubs, n.d.).

"Hubs," (n.d.) provides a comprehensive breakdown of the various 3D printing technologies:

> - **Powder Bed Fusion:** A high-power laser (in DMLS/SLM) or an electron beam (in EBM) is used to selectively bond metal powder particles together, layer-by-layer forming the metal part.
> - **Binder Jetting:** Metal powder particles are bound together with an adhesive layer-by-layer, forming an [unfinished] part that needs to

be thermally post-processed (sintered) to remove the binder and create a fully-metal part.

- **Metal Material Extrusion:** A filament or rod consisting of polymer and heavily loaded with metal powder is extruded through a nozzle (like in FDM) to form the [unfinished] part that is post-processed (debinded and sintered) to create a fully-metal part.
- **Direct Energy Deposition:** Metal powder or wire is melted by a high energy source and selectively deposited layer by layer.
- **Ultrasonic Additive Manufacturing:** Metal foils are bonded layer-by-layer using ultrasonic welding and then formed to the design shape using CNC machining. (Hubs, n.d.)

An important aspect of 3D printing is how long the production process takes, or production lead time. In the case of metal 3D printers, manufacturing and finishing a printed part typically takes at least 48 hours and an average 5 days (Hubs, n.d.-a). This is a key parameter in comparing the lead time in 3D printing a metal DLR and the estimated delivery date for a DLR placed on order through the supply system. 3D printing certain F/A-18E/F parts may be quicker than the time it takes to receive a part through the supply system.

Another timeframe to factor in with 3D printing is the post-process and finishing of the part. Post-processing and finishing requirements account for the remaining production time. Thermal treatments take up a large amount of time in the whole production process: a typical thermal cycle lasts 10 to 12 hours (Hubs, n.d.-a). Similar to the initial printing process, the finishing time needs to be taken into consideration when determining if 3D printing a part is quicker than the time it takes for a part to arrive via the supply system.

4. Polymer 3D Printing

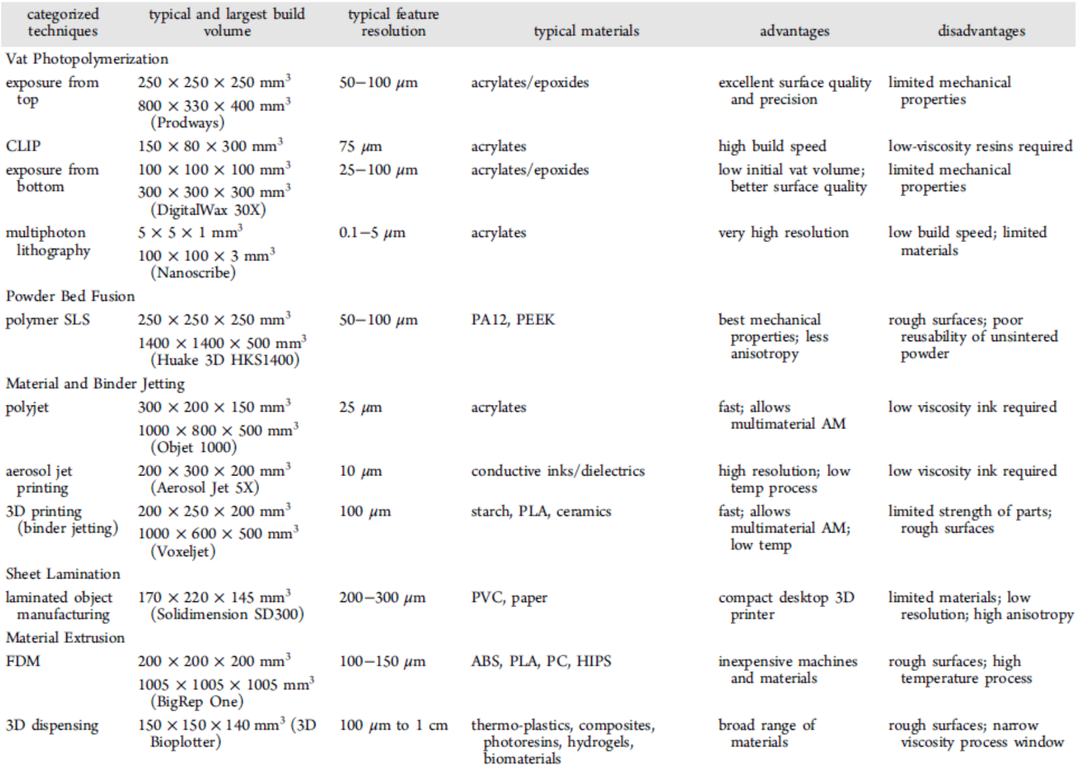
Many of the higher assembly parts of an F/A-18E/F are made up of polymers. Being able to 3D print polymers would potentially be important to ensure mission capability. This is beneficial since it allows for a cheaper option and flexibility to produce high priority parts needed for the F/A-18E/F (Arefin et al., 2021).

There are multiple methods to 3D print items using polymers. AM techniques for polymers include "vat photopolymerization (stereolithography), powder bed fusion (SLS), material and binder jetting (inkjet and aerosol 3D printing), sheet lamination (LOM), extrusion (FDM, 3D dispensing, 3D fiber deposition, and 3D plotting), and 3D bioprinting" (Ligon et al., 2017, p. 1). Ligon et al. (2017) breaks down the polymer AM techniques:

> - **Material extrusion** is an additive manufacturing process in which material is selectively dispensed through a nozzle. Fused deposition modeling (FDM), fused filament fabrication (FFF), 3D dispensing, and 3D bioplotting fall into this category.
> - **Material jetting** is an additive manufacturing process in which droplets of build material (such as photopolymer or thermoplastic materials) are selectively deposited. Systems based on inkjet-printing fall into this category.
> - **Binder jetting** is an additive manufacturing process in which a liquid bonding agent is selectively deposited to fuse powder materials.
> - **Sheet lamination** is an additive manufacturing process in which sheets of material are bonded together to form an object.
> - **Vat photopolymerization** is an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. Many of the lithography-based AM approaches (e.g., multiphoton polymerization (2PP), digital light processing (DLP), and stereolithography (SLA)) can be grouped into this category.
> - **Powder bed fusion** is an additive manufacturing process in which thermal energy (provided, e.g., by a laser or an electron beam) selectively fuses regions of a powder bed. Selective laser sintering (from 3D Systems) and laser sintering (from EOS), both of which are abbreviated in this Review as SLS, and electron beam machining (EBM) fall into this category. These processes are used for metals as well as polymers.
> - **Directed energy** deposition is an additive manufacturing process in which focused thermal energy (e.g., laser or plasma arc) is used to fuse materials by melting as they are being deposited. This process is currently only used for metals. (Ligon et al., 2017)

Table 1 from Ligon et al. (2017) shows the categorized AM techniques for polymers as well as advantages and disadvantages:

Table 1. Descriptions of Various AM Techniques. Source: Ligon et al. (2017).



categorized techniques	typical and largest build volume	typical feature resolution	typical materials	advantages	disadvantages
Vat Photopolymerization					
exposure from top	250 × 250 × 250 mm^3 800 × 330 × 400 mm^3 (Prodways)	50–100 μm	acrylates/epoxides	excellent surface quality and precision	limited mechanical properties
CLIP	150 × 80 × 300 mm^3	75 μm	acrylates	high build speed	low-viscosity resins required
exposure from bottom	100 × 100 × 100 mm^3 300 × 300 × 300 mm^3 (DigitalWax 30X)	25–100 μm	acrylates/epoxides	low initial vat volume; better surface quality	limited mechanical properties
multiphoton lithography	5 × 5 × 1 mm^3 100 × 100 × 3 mm^3 (Nanoscribe)	0.1–5 μm	acrylates	very high resolution	low build speed; limited materials
Powder Bed Fusion					
polymer SLS	250 × 250 × 250 mm^3 1400 × 1400 × 500 mm^3 (Huake 3D HKS1400)	50–100 μm	PA12, PEEK	best mechanical properties; less anisotropy	rough surfaces; poor reusability of unsintered powder
Material and Binder Jetting					
polyjet	300 × 200 × 150 mm^3 1000 × 800 × 500 mm^3 (Objet 1000)	25 μm	acrylates	fast; allows multimaterial AM	low viscosity ink required
aerosol jet printing	200 × 300 × 200 mm^3 (Aerosol Jet 5X)	10 μm	conductive inks/dielectrics	high resolution; low temp process	low viscosity ink required
3D printing (binder jetting)	200 × 250 × 200 mm^3 1000 × 600 × 500 mm^3 (Voxeljet)	100 μm	starch, PLA, ceramics	fast; allows multimaterial AM; low temp	limited strength of parts; rough surfaces
Sheet Lamination					
laminated object manufacturing	170 × 220 × 145 mm^3 (Solidimension SD300)	200–300 μm	PVC, paper	compact desktop 3D printer	limited materials; low resolution; high anisotropy
Material Extrusion					
FDM	200 × 200 × 200 mm^3 1005 × 1005 × 1005 mm^3 (BigRep One)	100–150 μm	ABS, PLA, PC, HIPS	inexpensive machines and materials	rough surfaces; high temperature process
3D dispensing	150 × 150 × 140 mm^3 (3D Bioplotter)	100 μm to 1 cm	thermo-plastics, composites, photoresins, hydrogels, biomaterials	broad range of materials	rough surfaces; narrow viscosity process window

5. 3D Printing Software

A 3D printer is not able to automatically print a part without software and a computer aided design (CAD) model of the part. Software is the foundation of 3D printing, and there are numerous tools to assist with designing and printing using 3D modelling (Hubs, n.d.-b). Having the software to develop F/A-18E/F parts is vital to support manufacturing endeavors and fulfill potential benefits of the 3D printed parts.

6. 3D Printing Parameter Settings

3D printers have different parameter settings which influence the print speed and quality of the build. Ultimately, a 3D printer's printing speed can be limited by nozzle movement speed as it maneuvers around the part to print each layer of thermoplastic filament (Dwamena, n.d.). Typically, the slower the printing speed, the better quality of the final product (Dwamena, n.d.). Printing speed is very important in determining the potential benefit of 3D printing being a quicker process than the status quo.

Print speed can be changed manually and directly influences the speed of the infill, wall, outer, and inner walls (Dwamena, n.d.). “Print speed settings help with improving print quality, making sure your part’s dimensional accuracy is on point, strengthening your prints, and helping reduce problems such as warping or curling” (Dwamena, n.d.). Quality and accuracy are important when producing F/A-18E/F parts since even just a slight deviation in dimensions can put the aircraft at risk if installed. Accuracy, strength, and quality are all affected by printing speed and is important in finding a good balance of speed settings. For example, if a 3D printer is producing poor quality and accuracy, reducing “the printing speed by 20–30 mm/s” can improve the results (Dwamena, n.d.).

Increasing speed can sometimes be detrimental to the printing process. As speed increases, the nozzle can become twitchy and lead to a flawed final product. Reducing travel speed and decreasing print speed should increase printing success rate and improve the overall print quality and dimensionally accuracy. The different types of 3D printing technologies also contribute to varying speed and quality. Another factor of print speed and quality is the type of material. Not every material is the same, and some materials are easier for the printer to render than others. Essentially, having a greater quality printer with appropriate settings can yield a better final product.

Shapeways is a company that offers various 3D printing services. Table 2 consolidates their website provides the estimated ranges for various types of AM technologies (Shapeways, n.d.):

Table 2. 3D Printing Estimates. Source: Shapeways (n.d.).

Material	**Min. Days**	**Max. Days**
Plastics	3	10
Steel	9	11
Aluminum	15	15
Platinum	11	11
Gold	9	18
Silver	19	23
Brass	16	20
Bronze	16	20

C. THE NAVAL AVIATION MAINTENANCE PROGRAM

This section provides prevalent background regarding naval aviation maintenance. The NAMP is the presiding document that governs all aspects of naval aviation maintenance. Based on technical difficulty, depth, scope, and range of work completed, the NAMP categorizes maintenance into three tiers. Organizational (O-level), Intermediate (I-level), and Depot (D-level) are the three levels (Naval Air Systems Command [NAVAIR], 2021). By and large, the O-level is considered to be squadron maintenance, maintenance actions performed on a day-to-day basis. Inspections, maintenance, and upkeep are limited in scope and requirements. I-level maintenance include intermediate maintenance activities (IMAs) and generally consists of repairing aeronautical components. Lastly, D-level maintenance and rework is conducted on aircraft, equipment, and material that requires overhaul, upgrading, or rebuilding of components, assemblies, subassemblies, and end items, as well as the manufacturing, modification, testing, and reclamation of parts, by specified depot activities (NAVAIR, 2021, p. 3-1).

An aircraft can be considered NMC for one of two reasons: either NMCM or NMCS. Aircraft reported as NMCM are considered inoperable due to a pending maintenance action. Aircraft reported as NMCS are considered inoperable due to a pending part requisition. While both metrics are key to accurate readiness reporting, NMCM work orders typically do not have the same impact as the NMCS because NMCM are generally limited to the squadron maintenance capacities. Comparatively, NMCS gripes accumulate and endure longer because their resolutions rely on capabilities of the supply system.

1. Component Repair Process

The ability to repair a repairable part is crucial in determining if it is a potential candidate for 3D printing. The current aviation maintenance process usually occurs as follows: after a part breaks or malfunctions, the non–ready-for-issue (RFI) part is sent to the I-level to determine if the part can be repaired by them. If I-level determines they cannot repair the part, then it is turned over to the supply system in exchange for a replacement. The broken part is then sent to the depot to be repaired. A common issue that occurs is that supply may not have a replacement part in stock due to it being on backorder or awaiting a contract delivery date. Lead times for the part can vary from 1 day to years, depending on availability (Government Accountability Office [GAO], 2007).

Production control is an important factor in determining component repair capability. NAVAIR (2021) details the production control process:

> For all components with Source Maintenance and Recoverability (SM&R) code indicating I-level capability, Production Control will direct repair to the full extent of the IMA's capabilities. Non-RFI field-level repairables (FLRs) with SM&R code PAOOO will be processed through the IMA for review to potential to repair. IMAs will perform test, check, and repair items covered under a performance-based logistics (PBL) contract to the extent specified in the SM&R code. If a PBL item has an SM&R code with a "G" or "H" in the fourth position, the IMA will test and repair the item per the specifications in applicable I-level technical manuals. (NAVAIR, 2021)

Table 3 shows how SM&R codes determine capability:

Table 3. SM&R Code Reference Table. Source: Headquarters, the Departments of the Army, the Navy, and the Air Force (2020).

JOINT SERVICE CODING REFERENCE CHART									
Source			Maintenance				Recoverability		
1st Position	2nd Position		3rd Position		4th Position		5th Position		6th Position
Means of Acquiring Support									
P	A	Item: Stocked.							SERVICE OPTION CODES
	B	Item: Stocked, insurance.	Use: Activity authorized to remove/replace the item.		Repair: Activity with capability to perform complete repair action.		Disposition: When unserviceable or uneconomically repairable, condemn or dispose.		
	C	Item: Stocked, deteriorative.							
	D	Item: Support, initial issue or outfitting and stocked only for additional initial issue.							
	E	Equipment: Support, initial issue or outfitting and stocked only for additional initial issue.							
	F	Equipment: Support, non-stocked, centrally procured on demand.	C O	Operator/Crew Organization/ unit	C O	Operator/Crew Organization/ unit	C O	Operator/Crew Organization/ unit	
	G	Item: Stocked for sustained support, uneconomical to produce at a later time.			F	Installation/ field/ intermediate level or afloat	F	Installation/ field/ intermediate level or afloat	
	H	Item: Stocked, contains hazardous materials, Hazardous Materials Information System/Material Safety Data Sheet reporting required.	F	Installation/ field/ intermediate level or afloat					
	R	Terminal or obsolete: Replaced.			G	Ashore and afloat	G	Ashore and afloat	
	Z	Terminal or obsolete: Not replaced.	G	Both ashore and afloat					
K	D	Item: Depot on hand and maintenance kits.			H	Installation/ field/ sustainment or ashore	H	Installation/ field/ sustainment or ashore	
	F	Item: Maintenance kit, place at O, F, H, L.							
	B	Item: In both depot repair and maintenance kits.							
M	O	Manufacture or fabricate at unit level.	H	Installation/ field/ sustainment or ashore					
	F	Manufacture or fabricate at intermediate/ field level.			K	Contractor facility	K	Contractor facility	
	H	Manufacture or fabricate at intermediate/ sustainment level.							
	L	Manufacture or fabricate at specialized repair activity.							
	G	Manufacture or fabricate at both afloat or ashore.	K	Contractor facility					
	D	Manufacture or fabricate at depot maintenance level.			L	Specialized repair activity	L	Not authorized below depot level	
A	O	Item: Assembled at unit.							
	F	Item: Assembled at intermediate/field level.							
	H	Item: Assembled at intermediate/ sustainment level.							
	L	Item: Assembled at specialized repair activity.	L	Specialized repair activity	D	Depot	D	Field level repairable: Condemn or dispose at depot	
	G	Item: Assembled afloat or ashore.							
	D	Item: Assembled at depot maintenance level.							
X	A	Item: Requisition next higher assembly.	D	Depot	Z	Non-repairable	Z	Non-repairable	
	B	Item: Not procured or stocked, available thru salvage. Requisition by cage/part number.							
	C	Manufacturer/installation drawing, diagram, instruction sheet: Identify by cage/part number.	Z	Reference only	B	Recondition	A	Requires special handling	
	D	Non-stocked: Obtain via local purchase.							

2. Beyond Capability of Maintenance

If the I-level determines they cannot repair a part, they assign it with a beyond capability of maintenance (BCM) code indicating the reason for their inability to repair (NAVAIR, 2021). “Production Control is responsible for applying the most appropriate BCM code to components that cannot be repaired” (NAVAIR,2021).

D. PART ISSUE AND RETURN PROCESS (SUPPLY)

The Aviation Support Detachment (ASD) is responsible for issuing, receiving, and inventorying various aircraft components to include the AVDLR’s. ASD is comprised of two sections: Supply Response Section (SRS) and Component Control Section (CCS), both are responsible for providing supply support for O- and I-level maintenance activities. ASD, as well as all of its functional elements, are staffed and operational during the same hours as the supporting maintenance organizations (“NAMP,” 2021). In other words, supply support is required 24 hours a day if maintenance is conducted 24 hours a day. Other than usual working hours, manning levels shall be consistent with the amount of support necessary and request processing criteria (“NAMP,” 2021). According to the “NAMP” (2021), key ASD functions include:

- Receive requests for material.
- Pick up and deliver material.
- Measure Supply response time.
- Account for all repairable assets.
- Maintain special Local Repair Cycle Assets (LRCA) storage areas and publish listings.
- Establish, maintain, and replenish (Pre-expended Bin) PEBs and their listings.
- Initiate inter-IMA repair and return service requests.
- Maintain Awaiting Parts (AWP) storage areas, control requisitions and piece parts, and initiate follow-ups on outstanding requisitions.
- Expedite high priority requisitions.
- Initiate all D-level customer service requests that are not initiated by the IMA. ASDs will initiate D-level customer service if:
- NMCS, PMCS, or work stoppage documents exist.
- The unserviceable exchange item requires D-level check and test.
- Available Supply System asset status indicates that a replacement is not now available. ASD will interrogate the Inventory Control Point (ICP) (if feasible) to determine system availability.
- Process specific customer service requests initiated by customers or IMAs requiring support for repair of repairables or depot manufacture of parts, providing an NMCS, PMCS, or work stoppage requirement exists. (“NAMP,” 2021)

SRS is part of the ASD and is responsible for handling maintenance material requests. “Requisition Control Unit (RCU), Technical Research Unit (TRU), Material Delivery Unit (MDU), Program Management Unit (PMU), and Pre-Expended Bin (PEB)” Unit are the five units that make up SRS (“NAMP,” 2021). The RCU of SRS is responsible for receiving material requisitions. Not in Stock (NIS) and Not Carried (NC) will be “automatically referred to the supply system through [an] electronic interface” (“NAMP,” 2021). After receiving a warehouse refusal, all NRFI material is automatically referred to the Supply System for processing and NALCOMIS is updated with referral status (“NAMP,” 2021). The Program Management Unit (PMU), which reports to SRS, is in charge of “processing and expediting high-priority requisitions such as NMCS or PMCS, Broad Arrow, and work stoppage requirements” (“NAMP,” 2021).

A process map detailing the functional relationships between the various elements of ASD within the grand scheme of the aviation maintenance and supply process can be found in the Appendix.

III. METHODOLOGY

The purpose of the methodology section is to detail the research, the data and the modeling process. This section provides the scope of this study and an overview of the methodology. A detailed review of the data and its implementation is explained, specifically using data from the F/A-18E/F. Additionally, assumptions and acknowledged limitations are addressed. Finally, the method of process mapping and how it was applied to this research is explained.

A. SCOPE

This research effort examined the expected requirements of AM with regards to the naval aviation maintenance of the Boeing F/A-18E and F/A-18F Super Hornet’s AVDLR. The F/A-18E/F served as a prime research subject for two predominant purposes. As explained in previous sections, these aircraft face a host of relevant and real-world logistical issues that undoubtedly affect mission readiness. In addition to its relevance, extensive requisition data for F/A-18E/F DLRs was easily obtainable. With regard to the data, this research focuses on the NMCS dispositioned AVDLRs to not only better manage the vast amount of data and to inform the practical and logical application of AM at the I-level.

B. METHODOLOGY OVERVIEW

This section details the methodology utilized for the research and explains the data sources and modeling/simulation process. As previously identified, this research aims to quantitively approximate the effects of AM on weapon repairable assembly (WRA) lead times by utilizing controlled scenarios. The data utilized for this research was filtered and narrowed to resemble the aviation maintenance and supply processes within the geographic bounds of Naval Air Station (NAS) Lemoore. To do so, requisition and repair data were collected from squadrons located within NAS Lemoore and Fleet Readiness Center (FRC)–West. After collecting the data, the research was facilitated by mapping out the aviation maintenance and supply processes first. This process was then modelled in Microsoft Excel and the expected values of total lead time is used to compare scenarios.

C. DATA SOURCES

1. DECKPLATE: NMCS Status for AVDLR

The bulk of the data was retrieved from DATAVIS, which is a data analysis platform that compiles data from fleet data sources such as DECKPLATE and AMSRR. DATAVIS serves as a conduit to draw reports from pertinent databases. In this case, the tailored report pulled was drawn for NAVAIR's DECKPLATE database, which serves as a repository of data drawn from OOMA NALCOMIS. The specific dashboard utilized for this research was the "PsILS" dashboard. The PsILS has several metrics for monthly Open, Closed, and "Sustainment" metrics—which compares Cannibalizations, Requisitions, and Direct Maintenance Manhours for Fiscal Year (FY) 2021. The dashboard was filtered to display F/A-18E/F Closed Requisitions with COG codes of 7R and the status code of NMCS. The 7R COG code indicates that the parts are AVDLR, and the NMCS status code indicates that the aircraft WRA is negatively afflicting the material condition of an F/A-18E/F, preventing it from flying and completing its mission. Within the columns of the raw data contained 16 categories, including Organizational Code (Org), Unit (Squadron), TMS, Bureau Number (BUNO or tail number), Status, DDSN, Order Date, Receipt Date, Days, Requisition Number, Job Control Number, National Item Identification Number (NIIN), COG, Item Name, and Unit Price.

Once exported to Excel, the data was filtered to only display the requisitions of the Super Hornet squadrons that are geographically located at NAS Lemoore. The NIIN and the "Days" data columns were used in this analysis. Once the file was appropriately filtered, it contained approximately 4,700 individual requisitions.

2. CNAF-AFAST Cost Analysis Database: Lead Time at FRC

The second data set utilized for this research was exported from the CNAF-AFAST Cost Analysis Database for NAS Lemoore. This Microsoft Access database compiled all Maintenance Action Forms (MAFs) completed by FRC-West in December 2021 and January 2022. A Microsoft Excel file was exported from the database that contained a variety of information from approximately 16,000 individual MAFs. The columns containing the NIINs and the total days of MAF completion; this data column reflects the time, in days, that it took a work center within FRC-West to fully process the broken WRA.

D. Assumptions and Acknowledged Limitations

The following assumptions were made to produce a meaningful model considering the real-world complexities of naval aviation maintenance and supply.

- NMCS is assumed to bear the most weight in overall NMC statuses across the Super Hornet fleet. While it is possible for an aircraft to be considered down for NMCM reasons, practical reality dictates that a squadron is more likely to address the root issues creating the NMCM condition quickly compared to the NMCS issues that are largely out of the squadron's control and depend on the externalities of the supply system.

- All WRAs are successfully repaired within the process. In reality, a sizeable portion of WRAs can be assessed as BCM by the I-level based on certain criteria and are subsequently sent to either the depot level for more in-depth repair or disposal.

- The available inventory of RFI WRAs that are commonly held at the Aviation Supply Depot (ASD) at varying inventory levels are not included in the model.

- WRAs and shop repairable assemblies (SRAs) are readily available when the lead time is one day or less. In other words, a requisition or MAF completion time of one day or less is assumed to indicate that the NAS Lemoore ASD has the part in stock (locally available).

- All FRC-West MAFs required an SRA to be ordered and that this cumulative time is reflected within the FRC Lead time data. Furthermore, similar assumptions were made about the lead time threshold for SRAs in-stock only taking 1 day or less. This research does not account for the time associated with EMT for maintainers to perform typical actions such as troubleshooting, repair, assembly, and disassembly.

- This research does not consider engineering specifications and limitations in the application of current AM technologies. While there is a focus on specific AM methodologies that would best suit the repair and fabrication of AVDLR components based on general material composition and dimensions, this research does not analyze each requisition at the individual component level to determine if they are adequate candidates for AM based on engineering specifications. Additionally, this research subsequently disregards the SM&R codes for individual components and assumes that AM fabrication will theoretically occur at the I-level or D-level of maintenance.

Considering that the selected data set represents requisitions for FY2021, this research acknowledges the potential for skewed data because of supply chain disruptions caused by the COVID-19 pandemic.

E. PROCESS MAPPING

Figure 4 displays a simplified version of the aviation maintenance process previously detailed in earlier sections of this paper. Rather than detailing the time within each process step, the process map describes relationships and times along the specific branches of the process.

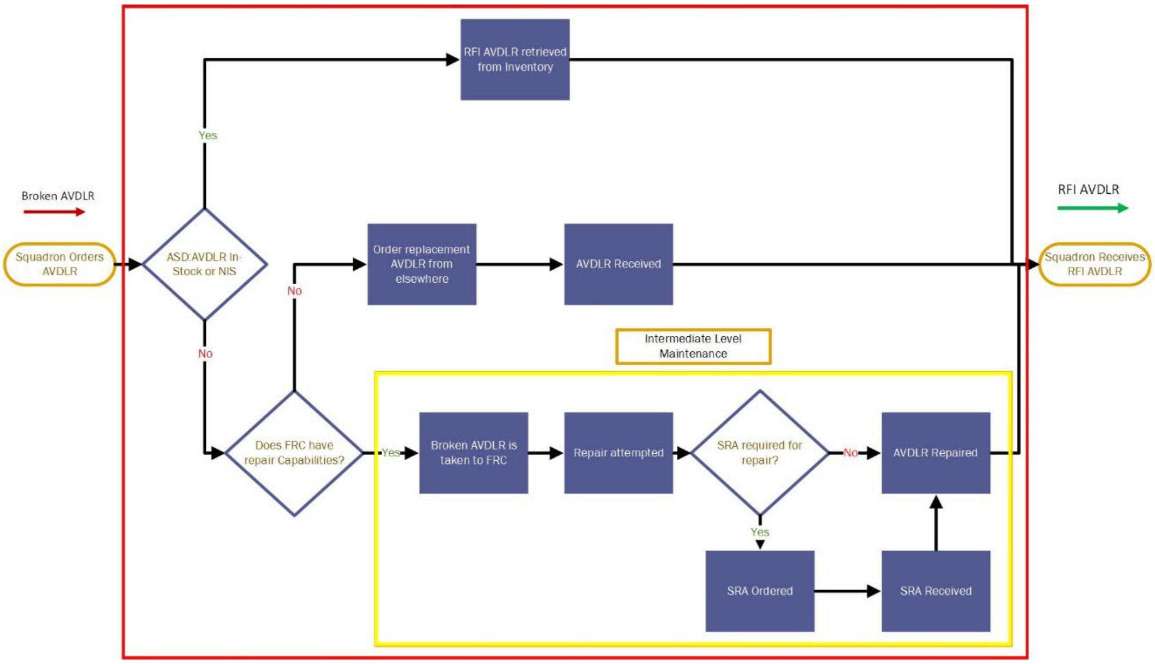


Figure 4. Simplified Naval Aviation Supply Process Map: Status Quo

F. SIMULATION DESCRIPTION

There are two study arms of this simulation experiment: Status Quo (i.e., the system as-is) and AM supported (i.e., the system with some component/sub-component demand met by AM). The key metric of this analysis is the total expected lead time. In other words, based on the data and assumptions, how long do squadrons wait for an RFI part after they turn their broken part into the local ASD? First, the model is described in the context of the Status Quo scenario, including a description of probability derivation using the relevant data. Then the AM interjected model changes and simulation effects are described.

1. Status Quo

The goal of the model is to simulate the aviation maintenance supply process and ultimately determine expected "lead time" (in days) observed from the squadron's perspective. The statistical principal of expected value (shown in the discrete form equation below) is used to calculate the total expected lead time. The expected value of a random variable (X) is summation over the entire sample space (I) of the product of the probability of an event or outcome (p_i) and the value of that event outcome (x_i).

$$\mathrm{E}[X] = \sum_{i \in I} p_i \, x_i$$

In the simulation model, x_i is the lead time of event i where i describes the end event from the process map branch: "AVDLR In Stock," "FRC No Capability," or "Subcomponent Required/Not Required" in Figure 4.

The lead time values (x_i) are generated randomly using Excel distribution functions that reflect the distribution of the corresponding lead time in the data. Therefore, each trial has unique, randomly generated lead times (x_i values) in accordance with the predetermined distributions.

a. Probability Derivation

Each probability is derived utilizing a combination of data sets and assumptions. Probabilities are needed for each decision node in the process map (identified by a diamond in Figure 4). The estimation of each probability is explained below.

The probability of FRC capability is only relevant for instances in which the AVDLR is NIS. Similarly, determining whether SRA is required for repair is dependent on whether FRC has capability. Therefore, the probabilities of FRC capability and SRA repair requirement are adjusted to reflect the dependencies.

(1) AVDLR In Stock or Not in Stock (NIS)

The assumption is that it takes the ASD one day or less to return a part to the squadron when they have it in stock. Thus, the probability of in stock versus NIS is derived by looking at the ratio of lead times within the squadron data set. The number of instances of "one or less" days divided by the total instances yields the probability of items in stock. The probability of NIS (one or more days) is the compliment of the probability of items in stock.

(2) Does the Aviation Intermediate Maintenance Department (AIMD) Have Capability (Yes/No)

These probabilities are derived by comparing the NIINs from the squadron requisition data set and the NIINs from the FRC-West data set. If the NIINs were found in both data sets, then FRC-West is assumed to have repair capability. Thus, the instances of FRC-matched NIINs divided by the total squadron NIINs is the probability that FRC-West has repair capability (denoted as “Yes” in Figure 4).

The probability of FRC not having the capability (denoted as “No” in Figure 4) is derived by comparing the mismatched NIINs on the squadron data set. This represents the ASD having to order the part for the squadron after determining that AIMD does not have the capability to repair it.

The probability of AIMD capability is adjusted by multiplying it by the prior “NIS” probability since AIMD capability is only relevant if the item is NIS.

(3) Is an SRA Required for Repair? (Yes/No)

Moving forward through the process branch, the yellow-outlined box in Figure 4 represents the expected time FRC-West needs to repair the part based on whether a subcomponent is needed. The assumption within this branch is that a NIIN with the associated lead time of 1 or less days did not require a subcomponent to be ordered.

The probability of SRA required repair is based on the previously identified list of NIINs that are associated with FRC-West’s repair capabilities. The number of instances of “1 or less” days divided by the total instances yields the probability that a subcomponent is not required. The probability of an SRA being required (more than 1 day) is the compliment of the lack of subcomponent requirement.

The probability of SRA required repair is adjusted by multiplying it by the adjusted “Does AIMD Have Capability? -Yes” probability since this only occurs in the instance AIMD has repair capability.

b. Lead Time Value Determination

The lead times (x_i values) of each step in the process branch in Figure 4 are selected each trial from the lead time distribution. A best-fit distribution was selected based on the relevant data attributes. This distribution is translated into Microsoft Excel as an inverse cumulative distribution function with an incorporated random number generator. Thus, a random lead time is generated based on the associated function and probability parameters. The lead time values generated in combination with the probabilities were used to calculate the expected value of the total lead time.

2. AM Supported Model Deviations

This model theoretically includes AM within the FRC-West repair process as drawn out by Figure 5. The model is nearly identical in structure to the previous with the following exception: the "FRC-West; SRA Required-Yes" data leads to a new branch dubbed "Is the SRA an AM Candidate Yes/No." This newly added portion of the model provides the FRC with an option to manufacture their own SRA by way of AM.

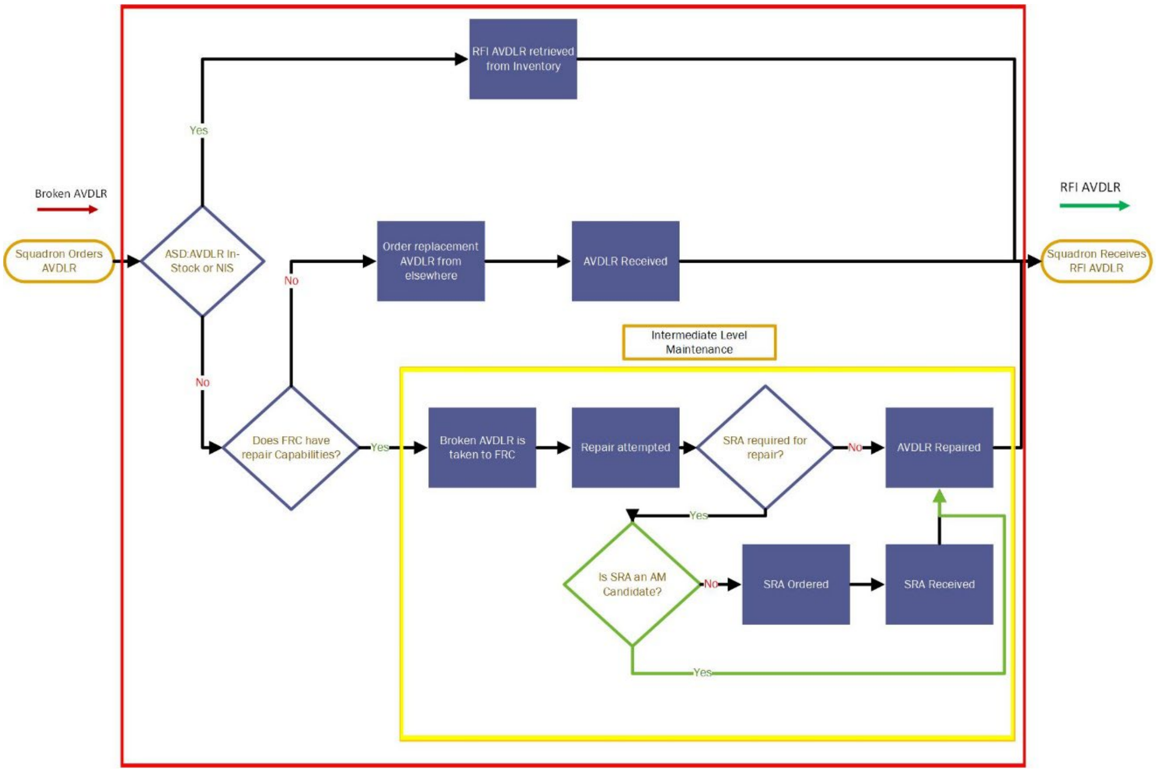


Figure 5. Simplified Naval Aviation Supply Process Map: AM at I-Level

In the AM interjected simulation model, x_i is the lead time of event i where i describes the end event from the process map branch in Figure 5: "AVDLR In Stock," "AIMD No Capability," "SRA Not Required," or "Is the Subcomponent an AM Candidate Yes/No." Parts navigating the new "AM candidate" branch in Figure 5 are parts where the lead times are "greater than 1 day" of the pertinent FRC-NIINs.

The AM model is consistent with the Status Quo model until the "AM Candidate" decision node (highlighted in yellow in Figure 5). The "AM candidate" node requires the probability a part is an AM candidate and the lead time if the component/sub-component is produced with AM.

(1) Probability Determination

AM candidacy by NIIN is outside the scope of this thesis. Therefore, a spectrum of probability scenarios was integrated within the AM candidacy portion of the model. The model provides scenarios for intervals of 5% from 5% to 90% of WRA parts utilizing AM.

In other words, the probability that a component/sub-component is an AM candidate ranges from 0.05 to 0.90.

(2) AM Lead Time Values

Each simulation incorporated an AM lead time value distribution from which a random lead time value would be derived from. The distributions utilized various AM lead time means and variances. The purpose of utilizing this type of variation throughout the overall experiment was to best simulate scenarios that reflect different AM capabilities and lead time possibilities. The AM lead time values taken from the Shapeways AM estimations served as the starting point for the creation of the various distributions (Shapeways, n.d.).

3. Simulation Experiment and Analysis

Microsoft Excel was the primary tool for facilitating both the model and the simulations within the experiment. The base model (Status Quo) was implemented into a single row within the trial sheet to best capture the variety of expected outputs within a singular trial. That one row is segmented into the steps of the process map; each segment is further segmented into probabilities, lead times, and the resulting expected value contribution for each process step. For the AM portion of the model, a spectrum of probabilities ranging from 5% to 90%, stepped up at 5% increments were built into the AM segment.

Eight different simulations were conducted throughout this experiment. Each simulation consisted of 100 trials and differed based on the associated AM lead time distributions. Each trial produced 19 expected value lead time outputs representing the outcome for each sub-scenario (Status Quo and various AM at I-level percentages). After running a set number of 100 trials, statistical data from the resulting tests were derived. Averages, minimums, maximums and confidence intervals were calculated for each expected lead time sub- scenario output across all 100 trials.

In terms of comparing the eight simulation results, each simulation’s 19 expected lead time averages were compiled into a single heatmap table for the purpose of trend analysis.

Along with the 100 trials conducted, model validation was conducted by employing one-tailed t-tests that compared the status quo outputs to the various AM percentage outputs in order to determine statistical significance.

Lastly, three of the eight simulations were analyzed by way of histograms. These histograms sorted the resultant expected lead time days into bins and compared their frequencies for the Status Quo 30%, 50%, and 90% expected lead time results. This type of analysis was conducted to illustrate aggregation of simulation results as well as conduct trend analysis. Three simulations were selected because they represented the most extreme differences in results amongst the eight experiments.

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IV. ANALYSIS

This section details the input parameters and numerical results from the simulations.

A. DATASET ANALYSIS RESULTS

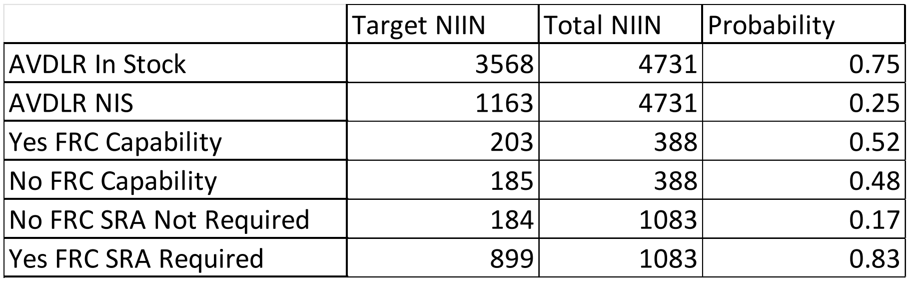
The foundational data consisted of the synthesis of two separate datasets. The F/A-18E/F requisition dataset yielded 4,731 individual requisitions of 391 NIINs once filtered for the targeted NAS Lemoore squadrons. The FRC-West maintenance dataset was comprised of 1,689 MAFs which consisted of 459 different NIINs.

The method of data sorting varied for each process step, but the underlying goal remained the same; isolate NIINs/Lead Time combinations relevant to that step, determine the probability by comparing that isolated data to the total body of applicable data (adjusting the probabilities when appropriate), and construct histograms of the select data to determine the best fit probability distributions.

1. Status Quo

Table 4 illustrates the Status Quo probabilities for each process step and their associated NIIN counts that contributed to the probability calculations:

Table 4. Status Quo Probabilities. Source: CNAF (2022); Fleetwood (2021).



	Target NIIN	Total NIIN	Probability
AVDLR In Stock	3568	4731	0.75
AVDLR NIS	1163	4731	0.25
Yes FRC Capability	203	388	0.52
No FRC Capability	185	388	0.48
No FRC SRA Not Required	184	1083	0.17
Yes FRC SRA Required	899	1083	0.83

The "Total NIIN" column represents the aggregate amount of NIINs from the relevant dataset while the "Target NIIN" column represents the filtered NIINs that were relevant to the corresponding process step. The "Probability" column informs the likelihood of the corresponding event occurrence within the model.

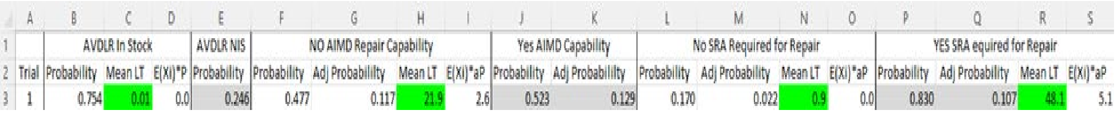
Next, probability distributions were derived using the filtered data for each of the relevant process steps. The Table 5 illustrates the statistical attributes of the filtered data as well as the selected best-fit probability distributions. A beta distribution best fit the lead time data for each branch.

Table 5. Status Quo Probability Distributions

	Applied Distribution	Average Lead Time	Min	Max	Alpha	Beta
AVDLR In Stock	Beta	0.12	0	1	1	6
No FRC Capability	Beta	19.97	2	97	1	5
FRC SRA Not Required	Beta	0.58	0	1	5	5
FRC SRA Required	Beta	47.75	1.02	600.0	0.6	8

These probability distributions served as the basis for the random lead time variables (x_i values) within the model. Data ranges for both the "No FRC Capability" and the "FRC SRA Required" data sets were shortened as they both contained outlier data points.

Figure 6 is a screenshot that reflects the layout of the Status Quo portion of the model:



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		AVDLR In Stock			AVDLR NIS	NO AIMD Repair Capability				Yes AIMD Capability		No SRA Required for Repair				YES SRA equired for Repair			
2	Trial	Probability	Mean LT	E(Xi)*P	Probability	Probability	Adj Probability	Mean LT	E(Xi)*aP	Probability	Adj Probability	Probability	Adj Probability	Mean LT	E(Xi)*aP	Probability	Adj Probability	Mean LT	E(Xi)*aP
3	1	0.754	0.01	0.0	0.246	0.477	0.117	21.9	2.6	0.523	0.129	0.170	0.022	0.9	0.0	0.830	0.107	48.1	5.1

Figure 6. Status Quo Portion of the Excel Model

2. AM Supported

The AM supported portion of the model utilizes the same values generated within the Status Quo portion. In addition to the Status Quo values, however, are the AM probabilities ranging from 5% to 90% as well as the AM distributions that output the random lead time variables (x_i values).

Table 6 displays the eight AM distributions that serve as the distinguishing factor for the eight simulations.

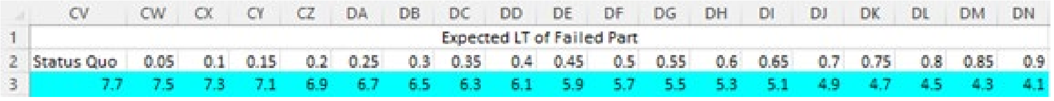
Table 6. AM Distributions

	Shorthand	Distribution	Min	Max	Average
AM Uniform R:(1-30)	AM Uni R:(1-30)	Uniform	1	30	15
AM Normal R:(1-30)	AM Norm R:(1-30)	Normal	1	30	15
AM Uniform R:(20-60)	AM Uni R:(20-60)	Uniform	20	60	40
AM Normal R:(20-60)	AM Norm R:(20-60)	Normal	20	60	40
AM Uniform R:(30-90)	AM Uni R:(30-90)	Uniform	30	90	60
AM Normal R:(30-90)	AM Norm R:(30-90)	Normal	30	90	60
AM Lognormal Left Skewed (15avg)	AM LogL (15avg)	Lognormal	-	-	15
AM Lognormal Right Skwed (25avg)	AM LogR (25avg)	Lognormal	-	-	25

The ranges and distribution patterns were selected to simulate various AM capabilities. The ranges of 1–30 days were meant to represent current capabilities as indicated by industry standards. The 20–30 days and the 30–60 days ranges were arbitrarily selected to represent medium and long lead times relative to the 1–30 day baseline. Uniform distributions were selected to serve as a theoretical baseline while the normal distributions were selected with the intent of simulating a central tendency around the averages. Lastly, the lognormal distributions were developed to mimic a tendency towards shorter lead times representing the production of plastics or slightly longer lead times representing metal production.

B. SIMULATION EXECUTION

The model culminates at the end of the trial row by cumulatively adding the expected values for each process step and displaying the summations for each sub-scenario of the trial as indicated by Figure 7.



	CV	CW	CX	CY	CZ	DA	DB	DC	DD	DE	DF	DG	DH	DI	DJ	DK	DL	DM	DN
1	Expected LT of Failed Part																		
2	Status Quo	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9
3	7.7	7.5	7.3	7.1	6.9	6.7	6.5	6.3	6.1	5.9	5.7	5.5	5.3	5.1	4.9	4.7	4.5	4.3	4.1

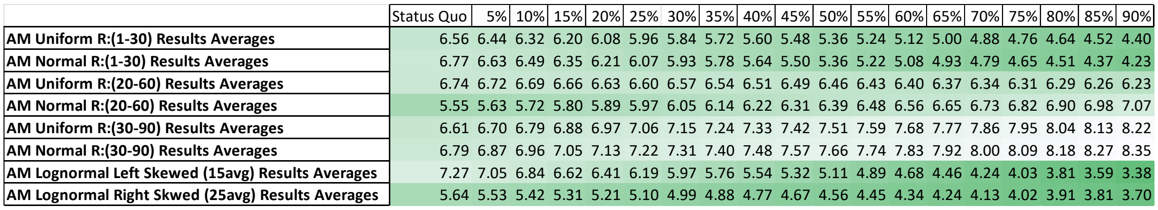
Figure 7. Excel Model Output

Ultimately, the model is designed in such a way that each trial outputs expected lead times that the squadron would experience under the 19 different sub-scenarios. Once the model was validated, a total of 100 trials were conducted for each of the eight simulations.

C. RESULTS

Statistical data was derived from the 100-trial simulations of each scenario. The heat map Table 7 displays the aggregated expected lead time averages.

Table 7. Expected Lead Average Heat Map



	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
AM Uniform R:(1-30) Results Averages	6.56	6.44	6.32	6.20	6.08	5.96	5.84	5.72	5.60	5.48	5.36	5.24	5.12	5.00	4.88	4.76	4.64	4.52	4.40
AM Normal R:(1-30) Results Averages	6.77	6.63	6.49	6.35	6.21	6.07	5.93	5.78	5.64	5.50	5.36	5.22	5.08	4.93	4.79	4.65	4.51	4.37	4.23
AM Uniform R:(20-60) Results Averages	6.74	6.72	6.69	6.66	6.63	6.60	6.57	6.54	6.51	6.49	6.46	6.43	6.40	6.37	6.34	6.31	6.29	6.26	6.23
AM Normal R:(20-60) Results Averages	5.55	5.63	5.72	5.80	5.89	5.97	6.05	6.14	6.22	6.31	6.39	6.48	6.56	6.65	6.73	6.82	6.90	6.98	7.07
AM Uniform R:(30-90) Results Averages	6.61	6.70	6.79	6.88	6.97	7.06	7.15	7.24	7.33	7.42	7.51	7.59	7.68	7.77	7.86	7.95	8.04	8.13	8.22
AM Normal R:(30-90) Results Averages	6.79	6.87	6.96	7.05	7.13	7.22	7.31	7.40	7.48	7.57	7.66	7.74	7.83	7.92	8.00	8.09	8.18	8.27	8.35
AM Lognormal Left Skewed (15avg) Results Averages	7.27	7.05	6.84	6.62	6.41	6.19	5.97	5.76	5.54	5.32	5.11	4.89	4.68	4.46	4.24	4.03	3.81	3.59	3.38
AM Lognormal Right Skwed (25avg) Results Averages	5.64	5.53	5.42	5.31	5.21	5.10	4.99	4.88	4.77	4.67	4.56	4.45	4.34	4.24	4.13	4.02	3.91	3.81	3.70

The heat map indicates that, in general, the AM distributions with 1–30 days ranges as well as the lognormal distributions steadily decreased in average lead time as the percentage of AM manufactured increased. Comparatively, the medium-normal (20-60) and both long (30-90) AM lead time distributions displayed an increase in average lead times.

A one tailed t-Test was conducted to determine statistical significance by comparing the Status Quo results to each of the AM percentage results for all eight simulations. Generally speaking, the p-values were consistent between the different simulations and displayed an increase in statistical significance as the AM percentages increased. The p-values can be viewed in the appendix section.

Histograms were created of the resulting outputs for the AM Uni R:(1-30), AM Uni R:(30-60), and the AM LogL(15avg) distributions. The histograms allocate the resultant simulation outputs into bins with a width of one day and total the occurrence frequency of the results within the bins. For example, results of 5.3 days would be placed into the "5" lead time day bin. The histograms are meant to show comparative trends between the Status Quo and the selected AM percentages for each of the three select simulations.

The histograms of Figures 8, 9, and 10 indicate a left-ward trend towards the lower lead time days as the percentage of AM lead time increases.

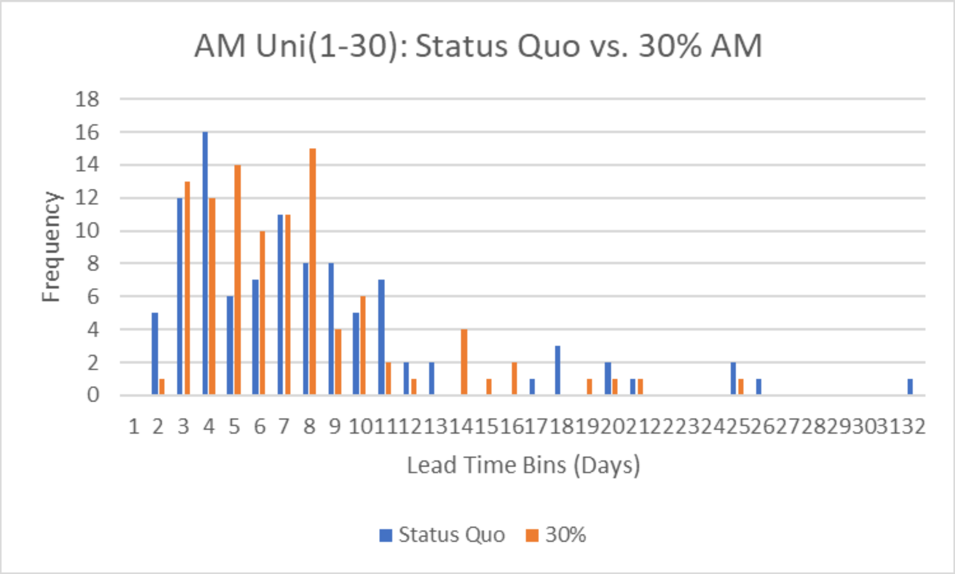


Figure 8. AM Uniform R(1-30): Status Quo vs. 30% AM Histogram

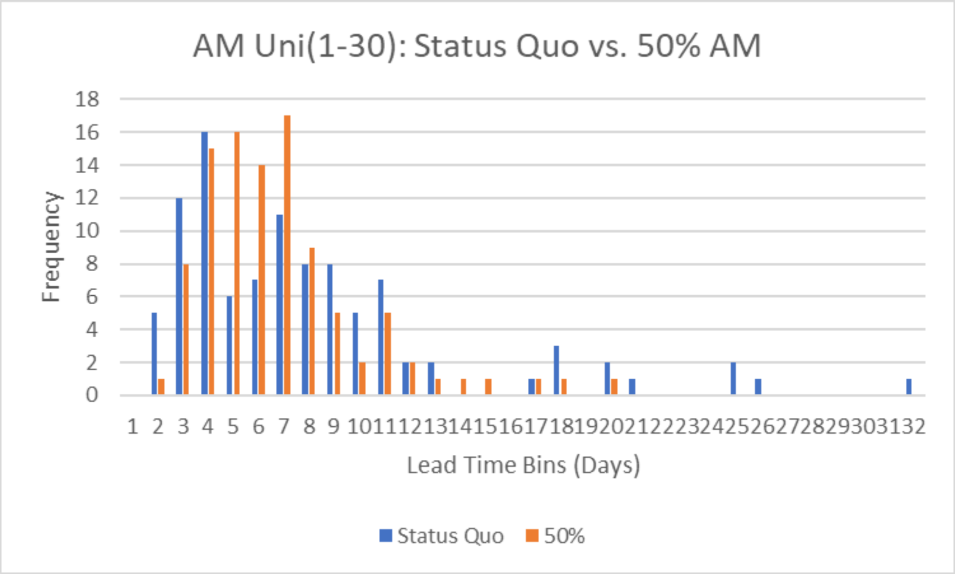


Figure 9. AM Uniform R(1-30): Status Quo vs. 50% AM Histogram

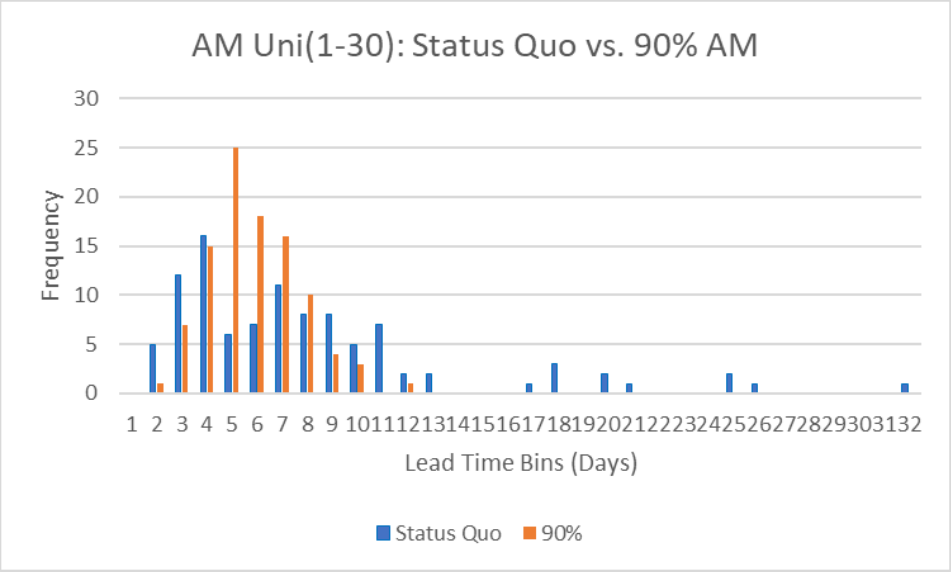


Figure 10. AM Uniform R(1-30): Status Quo vs. 90% AM Histogram

Compared to the AM Uniform R(1-30) histograms, the AM Uniform R(30-90) histograms in figures 11, 12, and 13 appear to exhibit an inverse trend in which the lead time days appeared to trend right-ward towards the longer lead times as the percentage of AM increased.

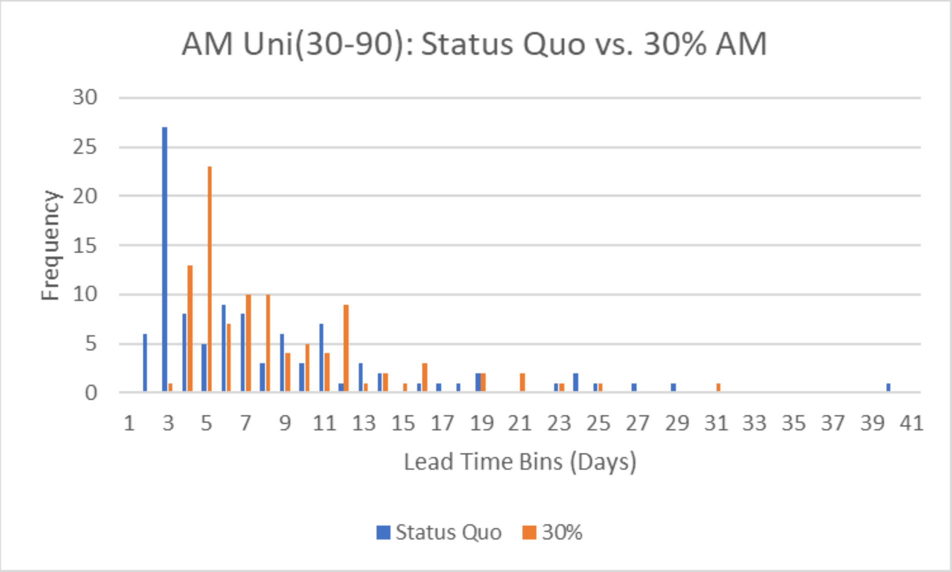


Figure 11. AM Uniform R(30-90): Status Quo vs. 30% AM Histogram

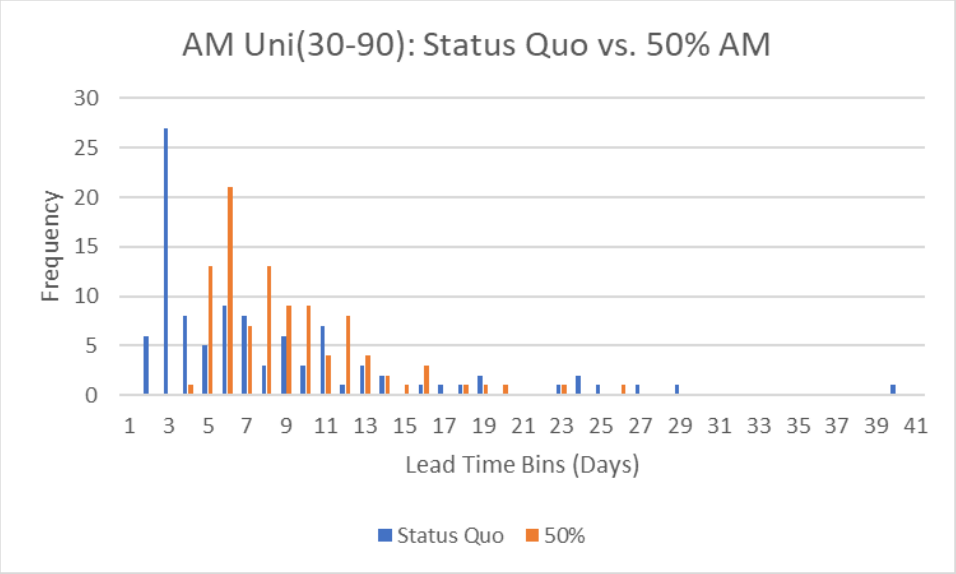


Figure 12. AM Uniform R(30-90): Status Quo vs. 50% AM Histogram

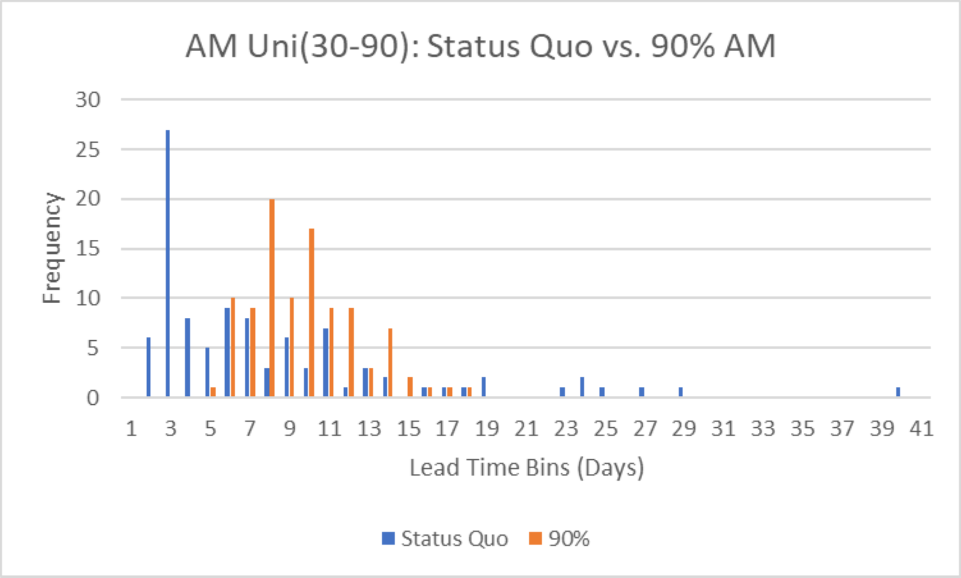


Figure 13. AM Uniform R(30-90): Status Quo vs. 90% AM Histogram

Figures 14, 15, and 16 representing the AM Lognormal Left Skewed (15avg) histogram displays a similar left-ward tendency as the AM Uniform R(1-30) histograms of Figures 8–10 but to a higher degree.

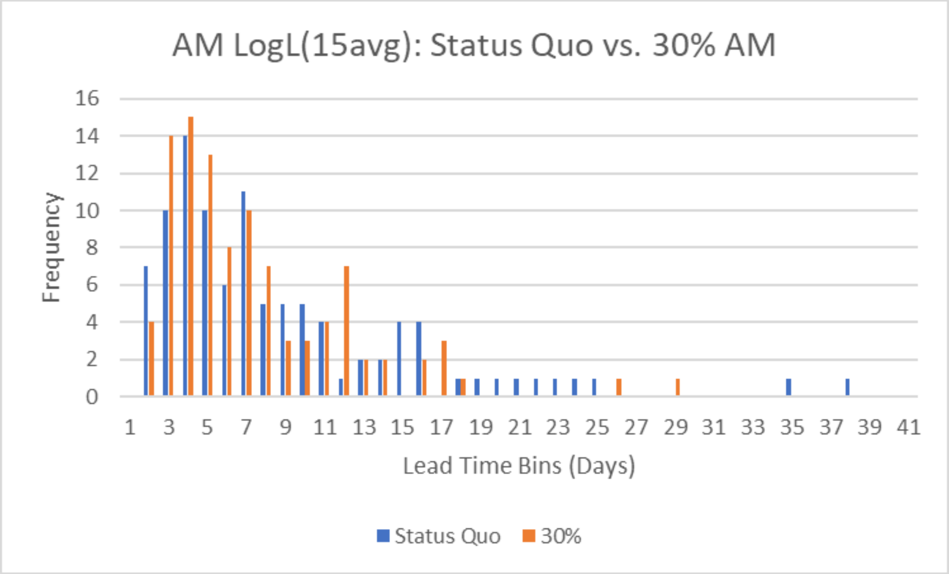


Figure 14. AM Lognormal Left Skewed (15avg): Status Quo vs. 30% Histogram

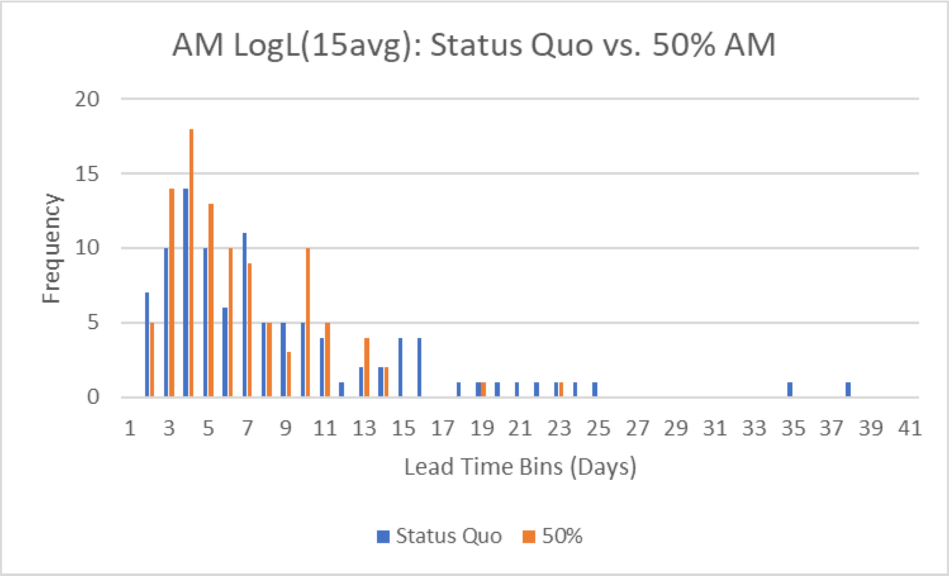


Figure 15. AM Lognormal Left Skewed (15avg): Status Quo vs. 50% Histogram

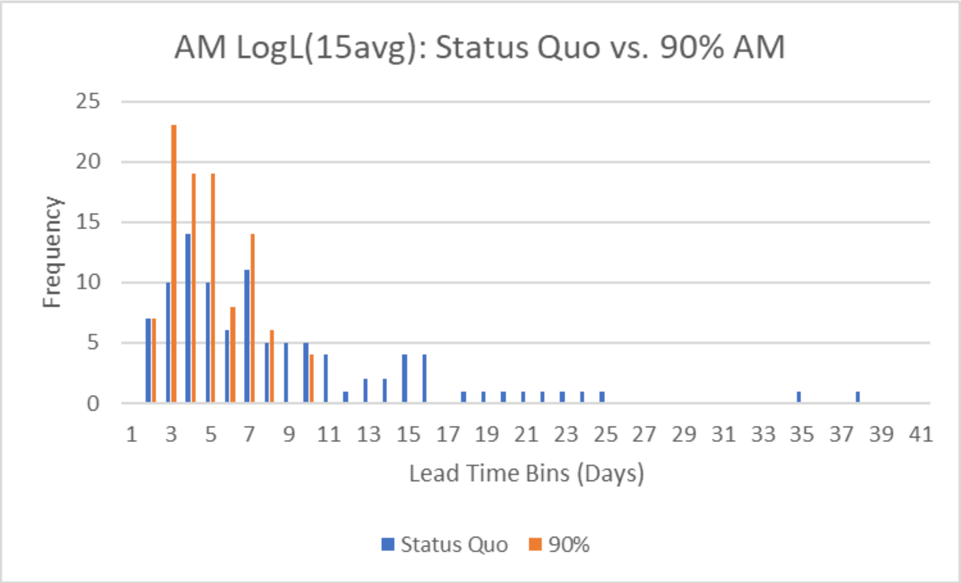


Figure 16. AM Lognormal Left Skewed (15avg): Status Quo vs. 90% Histogram

When these histograms are compared to each other, it is clear that the simulations in which AM takes less than 30 days yielded smaller overall lead times (in conjunction with increased AM percentages) relative to the simulation in which AM took longer than

30 days to produce. This observation probably indicates that within this controlled model, the longer AM lead times (30 days plus) are likely to increase overall lead times as AM becomes more prevalent in the process and represents a negative impact to the overall process.

A table displaying the compiled averages, minimums, maximums, standard deviations, confidence intervals, and one-tailed t-Test p-values for each sub-scenario is located in the appendix.

D. DISCUSSION

Looking at both the heatmap and the histogram analyses, the experiment suggests that longer AM lead times would negatively impact overall lead times as the percentage of AM produced increases. Conversely, the short 1–30-day lead times appeared to have a benefit as designed, the model seems to be effective in progressively decreasing the amount of expected lead time days. Upon analyzing the model's integrated process probabilities, it is worth noting that most of the squadron requisitions had relatively small lead times, thus accounting for a majority of the initial probabilities of the ASD either having the part readily available or ordering it when the FRC lacks the repair capability. In fact, an analysis of the 4,731 rows within the "Squadron Requisitions" dataset showed the following spread of lead times:

- 14 rows (0.3%) have lead time between 100–190 days
- 48 rows (1%) have lead time between 50–99 days
- 128 rows (2.7%) have lead time between 25–49 days
- 300 rows (6.3%) have lead time between 10–24 days
- 4241 rows (89.6%) have lead times 9 days or less

Even if AM was applied to the AVDLRs with historical lead times of 25 days or greater, this would only account for a relatively insignificant 4% portion of the overall dataset.

Looking at the yielded statistical data, it appears to exhibit a high degree of variability amongst all the sub-scenarios and scenarios. Upon further inspection of the confidence intervals, all the points seem to begin with larger confidence intervals starting with the Status Quo sub-scenario and gradually wanes as with each progressively increased increment AM sub-scenario. This indicates that the model has a higher degree of predictability as the AM levels increase.

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V. CONCLUSION

As detailed within the introduction and reiterated within the Literature Review sections, the F/A-18E/F Super Hornet is steadily experiencing reoccurring readiness issues that can partially be attributed to logistical challenges. AM shows the potential of helping these logistical challenges by revolutionizing the Naval aviation maintenance and supply process. This research utilized mathematical modeling (paired with real-world F/A-18E/F NMCS requisition and repair data) to theoretically interject AM into the Intermediate level maintenance process with the goal of comparing resultant expected lead time values for the various levels of AM production.

The observed model results between the eight different simulations progressively diverged as the AM production percentages increased. All four simulations that included random AM lead time distributions with 1–30 days resulted in a progressive decrease in total expected lead time as the AM production percentages increased. With the exception of one of the Uniform 20–60 day distribution, the remaining three simulations of consisting of longer AM lead times resulted in an increase in total expected lead times. The interpretation of this research's results suggests that AM can offer measurable benefits in AVDLR lead times when AM capabilities allow for production times of less than 30 days. This assessment is encouraging considering that current AM technologies, given the right equipment and materials, can produce most plastic and metal F/A-18E/F components in less than 30 days. This, in-turn, validates current endeavors to implement AM into military application. Subsequently, it stands to reason that the AM candidate pool must be large enough or would need to be predominantly faster in requisition fulfillment than the contemporary supply avenues. The results of the model and simulations suggests that predictability is more assured with increased amounts AM in the process. In other words, the more F/A-18E/F parts produced through AM, the more predictable the overall lead times become.

A. FUTURE CONSIDERATIONS

Considering that this case was relegated to the analysis one shore-based maintenance facility, decision makers will need to consider the impact that implementation of AM will have on a weapon system's entire maintenance-supply process to include operations on seagoing vessels. AM technologies and capabilities will continue to develop, and it is worth periodically assessing these developments in the context of 3D printing aviation parts for DOD aircraft.

For the purpose of this study, only F/A-18E/F Super Hornet parts were looked at for the application of AM. It would be worth looking at the other aircraft that fall under the DOD to determine the viability of AM and its potential to 3D print parts at a faster rate than receiving them via the supply chain status quo. It would also be helpful to look at the possible benefits of applying AM to surface parts, specifically seagoing vessels. Deployment can be difficult to receive parts in a timely manner and ordering them during this phase often results in long lead times. Looking at each class of U.S. Navy vessels and the most common high priority parts that are ordered and have long lead times should be considered for AM application. If viable candidates are determined for AM, the potential reduced lead time could increase readiness and ensure the crew can accomplish the mission while on deployment.

Separating the NMCS parts by composite and identifying the most common materials is something to consider. An operation may not be able to support having different types of printers but obtaining a printer for the most common type of composite is NMCS may produce positive results. It would be also worth comparing the percentage of each composite to the speed of the respective printers. For example, metal parts could potentially make up the majority of NMCS sub-assembly parts, but the printing speed may have a longer lead time than the status quo. However, the result could be the opposite for plastic sub-assembly parts. Choosing to print plastic parts could be considered over metal based on the potential findings of further research.

The model, simulation and analysis methodologies developed for this specific case can be further developed by fine-tuning assumptions and datasets and can be applied to any weapon system that relies on a supply system for replacement parts. Additionally, the methodology could be applied in AM candidacy considerations.

Although there have been studies conducted on the potential of cost savings from AM versus ordering a part through the supply system, it would be worth conducting studies that factors both cost savings and lead time. The model in this study determines viable candidates for AM to decrease lead time, however it still may be cheaper to order the part via the status quo. Further research could potentially determine viable candidates to 3D print that are both cheaper and have less of a lead time than the status quo.

This research can also be expanded to the effects on operational availability. While an analysis on cost and lead times does provide good information in specific areas it does not provide the overall picture. For one to find out the effects on operational availability could change the benefits or shortcomings of the other research.

Researching how often on average the different types of 3D printers become inoperable would be beneficial to determining the potential of reduced lead times from AM. It would also be worth researching how long on average it takes to fix a printer once it is out of service could also affect the viability of using AM for reduced lead time. If the current average is determined to be too frequent to see a reduction in lead time, then it may be best to wait for AM technologies to mature and revisit the research in the future.

B. FINAL WORDS

Undoubtedly, AM has the potential to improve readiness and subsequent readiness related costs in the future. Additionally, the prevalent issues surrounding F/A-18E/F readiness made it a prime use-case platform for this research project. While this experiment conducted through simulation was controlled in the sense of discounting certain realistic aspects, it gained benefit of applied real-world data. The result of this research suggests that current standing AM technologies, however, the opportunity exists to improve readiness with the steady implementation of AM processes, procedures, and technologies.

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APPENDIX

Table 8. AM Uniform R:(1-30) Results Table

AM Uniform R:(1-30) Results Table																			
	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	6.56	6.44	6.32	6.20	6.08	5.96	5.84	5.72	5.60	5.48	5.36	5.24	5.12	5.00	4.88	4.76	4.64	4.52	4.40
Min	0.63	0.74	0.85	0.93	0.93	0.92	0.91	0.91	0.90	0.90	0.89	0.88	0.88	0.87	0.86	0.86	0.85	0.85	0.84
Max	30.29	29.09	27.90	26.71	25.52	24.33	23.13	21.94	20.75	19.56	18.37	17.17	15.98	14.79	13.60	12.59	11.84	11.08	10.32
Std Dev	5.77	5.51	5.26	5.01	4.76	4.51	4.27	4.03	3.78	3.55	3.32	3.09	2.87	2.65	2.45	2.26	2.09	1.93	1.81
P-values	0.00	0.44	0.38	0.32	0.26	0.21	0.16	0.12	0.08	0.06	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Confidence Int	0.11	0.11	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
Lower Bound	6.44	6.33	6.22	6.10	5.99	5.87	5.76	5.64	5.53	5.41	5.30	5.18	5.07	4.95	4.83	4.72	4.60	4.49	4.37
Upper Bound	6.67	6.55	6.42	6.30	6.17	6.05	5.92	5.80	5.67	5.55	5.43	5.30	5.18	5.05	4.93	4.81	4.68	4.56	4.44

Table 9. AM Uniform R:(20-60) Results Table

AM Uniform R:(20-60) Results Table																			
	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	6.74	6.72	6.69	6.66	6.63	6.60	6.57	6.54	6.51	6.49	6.46	6.43	6.40	6.37	6.34	6.31	6.29	6.26	6.23
Min	0.44	0.61	0.78	0.94	1.11	1.28	1.45	1.62	1.79	1.96	2.12	2.29	2.46	2.63	2.67	2.70	2.74	2.77	2.81
Max	24.81	24.11	23.41	22.71	22.01	21.31	20.61	19.91	19.21	18.51	17.80	17.10	16.40	15.70	15.00	14.30	13.60	12.90	12.33
Std Dev	5.35	5.10	4.84	4.59	4.35	4.10	3.86	3.63	3.40	3.17	2.96	2.76	2.57	2.39	2.24	2.11	2.01	1.94	1.92
P-values		0.485	0.468	0.452	0.434	0.416	0.397	0.378	0.359	0.340	0.320	0.301	0.282	0.263	0.245	0.228	0.212	0.197	0.183
Confidence Int	0.10	0.10	0.09	0.09	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Lower Bound	6.64	6.62	6.59	6.57	6.54	6.52	6.50	6.47	6.45	6.42	6.40	6.37	6.35	6.32	6.30	6.27	6.25	6.22	6.19
Upper Bound	6.85	6.82	6.78	6.75	6.71	6.68	6.65	6.61	6.58	6.55	6.52	6.48	6.45	6.42	6.39	6.36	6.33	6.30	6.27

Table 10. AM Uniform R:(30-90) Results Table

AM Uniform R:(30-90) Results Table																			
	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	6.61	6.70	6.79	6.88	6.97	7.06	7.15	7.24	7.33	7.42	7.51	7.59	7.68	7.77	7.86	7.95	8.04	8.13	8.22
Min	0.40	0.66	0.92	1.18	1.44	1.70	1.96	2.22	2.49	2.75	2.99	3.09	3.18	3.28	3.38	3.47	3.57	3.67	3.77
Max	38.73	37.27	35.81	34.34	32.88	31.42	29.96	28.49	27.03	25.57	24.11	22.64	21.18	19.80	19.22	18.64	18.05	17.47	16.89
Std Dev	6.91	6.61	6.31	6.02	5.73	5.44	5.16	4.88	4.61	4.35	4.10	3.86	3.63	3.42	3.23	3.06	2.92	2.81	2.73
P-values	0.00	0.46	0.42	0.39	0.35	0.31	0.27	0.23	0.20	0.16	0.13	0.11	0.09	0.07	0.05	0.04	0.03	0.02	0.02
Confidence Int	0.135	0.130	0.124	0.118	0.112	0.107	0.101	0.096	0.090	0.085	0.080	0.076	0.071	0.067	0.063	0.060	0.057	0.055	0.054
Lower Bound	6.48	6.57	6.67	6.76	6.86	6.95	7.05	7.14	7.24	7.33	7.42	7.52	7.61	7.71	7.80	7.89	7.98	8.08	8.17
Upper Bound	6.75	6.83	6.91	7.00	7.08	7.17	7.25	7.33	7.42	7.50	7.59	7.67	7.75	7.84	7.93	8.01	8.10	8.19	8.27

Table 11. AM Normal R:(1-30) Results Table

AM Normal R:(1-30) Results Table

	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	6.77	6.63	6.49	6.35	6.21	6.07	5.93	5.78	5.64	5.50	5.36	5.22	5.08	4.93	4.79	4.65	4.51	4.37	4.23
Min	0.55	0.62	0.69	0.76	0.83	0.89	0.96	1.03	1.07	1.09	1.12	1.14	1.16	1.18	1.21	1.23	1.25	1.27	1.29
Max	22.99	21.89	20.80	19.70	18.60	17.51	16.41	15.31	14.21	13.12	12.02	10.96	10.53	10.44	10.35	10.26	10.17	10.08	9.99
Std Dev	4.90	4.68	4.45	4.23	4.01	3.79	3.58	3.37	3.17	2.98	2.80	2.62	2.46	2.32	2.19	2.09	2.01	1.96	1.94
P-values	0.00	0.42	0.33	0.26	0.19	0.13	0.08	0.05	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Confidence Int	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04
Lower Bound	6.68	6.54	6.40	6.27	6.13	5.99	5.85	5.72	5.58	5.44	5.30	5.17	5.03	4.89	4.75	4.61	4.47	4.33	4.19
Upper Bound	6.87	6.72	6.58	6.43	6.29	6.14	6.00	5.85	5.70	5.56	5.41	5.27	5.12	4.98	4.84	4.69	4.55	4.41	4.26

Table 12. AM Normal R:(20-60) Results Table

AM Normal R:(20-60) Results Table

	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	5.55	5.63	5.72	5.80	5.89	5.97	6.05	6.14	6.22	6.31	6.39	6.48	6.56	6.65	6.73	6.82	6.90	6.98	7.07
Min	0.32	0.65	0.84	1.02	1.11	1.19	1.28	1.37	1.45	1.54	1.63	1.72	1.80	1.89	1.98	2.06	2.15	2.24	2.32
Max	24.03	23.25	22.48	21.71	20.94	20.17	19.40	18.63	17.85	17.08	16.31	15.54	14.77	14.00	13.22	12.45	12.17	12.33	12.61
Std Dev	4.52	4.34	4.17	3.99	3.82	3.65	3.49	3.33	3.18	3.03	2.89	2.75	2.63	2.52	2.42	2.33	2.26	2.20	2.17
P-values	0.00	0.45	0.39	0.34	0.28	0.23	0.19	0.15	0.11	0.08	0.06	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00
Confidence Int	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04
Lower Bound	5.46	5.55	5.63	5.72	5.81	5.90	5.99	6.07	6.16	6.25	6.34	6.42	6.51	6.60	6.68	6.77	6.86	6.94	7.03
Upper Bound	5.64	5.72	5.80	5.88	5.96	6.04	6.12	6.20	6.29	6.37	6.45	6.53	6.61	6.70	6.78	6.86	6.94	7.03	7.11

Table 13. AM Normal R:(30-90) Results Table

AM Normal R:(30-90) Results Table

	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	6.79	6.87	6.96	7.05	7.13	7.22	7.31	7.40	7.48	7.57	7.66	7.74	7.83	7.92	8.00	8.09	8.18	8.27	8.35
Min	0.73	0.84	0.96	1.07	1.19	1.30	1.42	1.53	1.65	1.76	1.88	1.99	2.11	2.22	2.33	2.45	2.56	2.68	2.79
Max	26.25	25.30	24.35	23.40	22.45	21.49	20.54	19.59	18.64	17.69	17.05	16.48	15.91	15.35	14.78	14.21	13.64	13.07	12.60
Std Dev	5.23	4.99	4.75	4.51	4.28	4.05	3.82	3.60	3.39	3.18	2.99	2.80	2.63	2.47	2.33	2.21	2.12	2.06	2.04
P-values	0.00	0.45	0.40	0.35	0.30	0.26	0.21	0.17	0.13	0.10	0.08	0.05	0.04	0.03	0.02	0.01	0.01	0.00	0.00
Confidence Int	0.10	0.10	0.09	0.09	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04
Lower Bound	6.68	6.78	6.87	6.96	7.05	7.14	7.23	7.32	7.42	7.51	7.60	7.69	7.78	7.87	7.96	8.05	8.14	8.22	8.31
Upper Bound	6.89	6.97	7.05	7.14	7.22	7.30	7.38	7.47	7.55	7.63	7.71	7.80	7.88	7.97	8.05	8.13	8.22	8.31	8.39

Table 14. AM Lognormal Left Skewed (15avg) Results Table

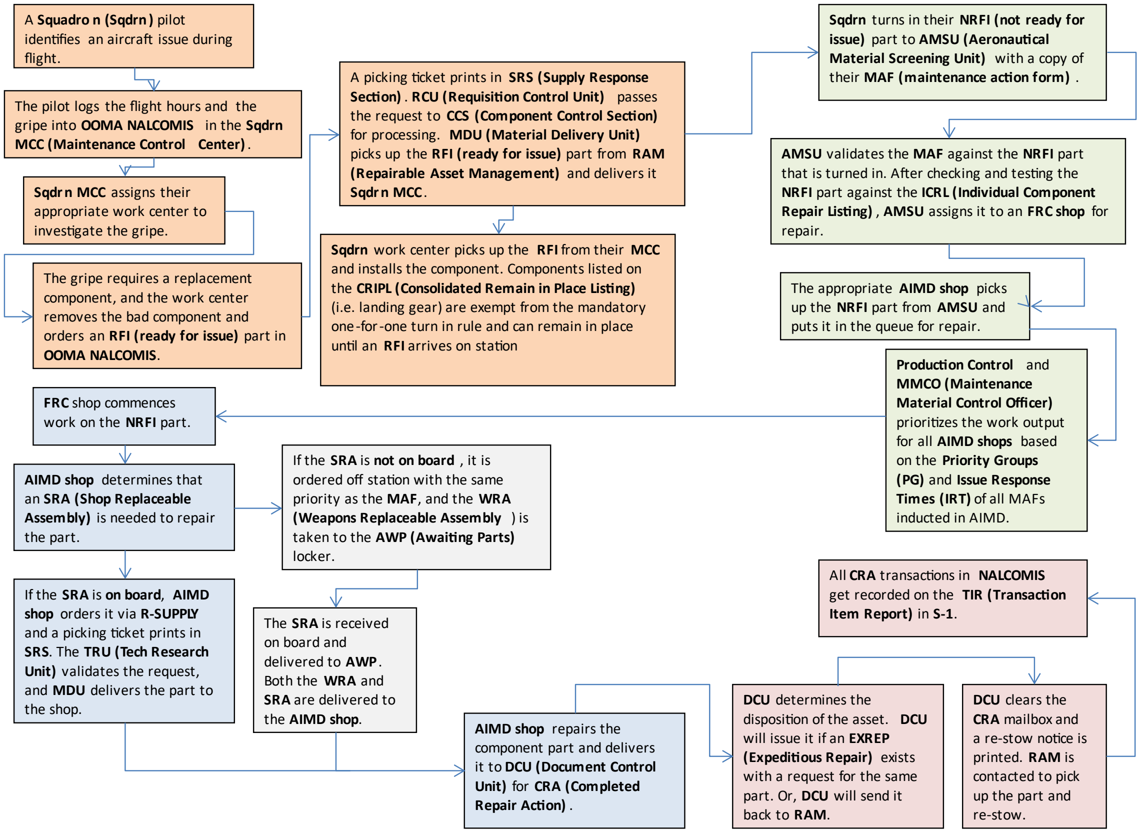
AM Lognormal Left Skewed (15avg) Results Table

	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	7.27	7.05	6.84	6.62	6.41	6.19	5.97	5.76	5.54	5.32	5.11	4.89	4.68	4.46	4.24	4.03	3.81	3.59	3.38
Min	0.54	0.63	0.64	0.64	0.64	0.65	0.65	0.65	0.66	0.66	0.66	0.67	0.67	0.67	0.65	0.63	0.60	0.55	0.50
Max	36.47	34.93	33.39	31.85	30.30	28.76	27.22	25.68	24.14	22.59	21.05	19.51	17.97	16.43	14.88	13.34	11.80	10.26	8.73
Std Dev	6.77	6.46	6.14	5.83	5.52	5.21	4.91	4.60	4.30	4.01	3.72	3.44	3.17	2.91	2.66	2.43	2.23	2.06	1.94
P-values	0.00	0.41	0.32	0.23	0.16	0.10	0.06	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Confidence Int	0.13	0.13	0.12	0.11	0.11	0.10	0.10	0.09	0.08	0.08	0.07	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04
Lower Bound	7.14	6.93	6.72	6.51	6.30	6.09	5.88	5.67	5.46	5.25	5.04	4.82	4.61	4.40	4.19	3.98	3.77	3.55	3.34
Upper Bound	7.40	7.18	6.96	6.74	6.51	6.29	6.07	5.85	5.62	5.40	5.18	4.96	4.74	4.52	4.30	4.07	3.85	3.63	3.42

Table 15. AM Lognormal Right Skewed (25avg) Results Table

AM Lognormal Right Skwed (25avg) Results Table

	Status Quo	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%
Avg	5.64	5.53	5.42	5.31	5.21	5.10	4.99	4.88	4.77	4.67	4.56	4.45	4.34	4.24	4.13	4.02	3.91	3.81	3.70
Min	0.75	0.76	0.78	0.79	0.81	0.83	0.84	0.86	0.87	0.89	0.91	0.92	0.94	0.95	0.97	0.98	0.96	0.95	0.90
Max	19.50	18.58	17.67	16.76	15.84	14.93	14.02	13.35	12.85	12.35	11.85	11.35	10.85	10.35	9.85	9.36	8.86	8.36	7.88
Std Dev	4.17	3.99	3.81	3.64	3.46	3.29	3.12	2.96	2.80	2.64	2.49	2.35	2.22	2.09	1.98	1.89	1.80	1.74	1.70
P-values	0.00	0.43	0.35	0.28	0.21	0.16	0.11	0.07	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Confidence Int	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03
Lower Bound	5.55	5.45	5.35	5.24	5.14	5.03	4.93	4.82	4.72	4.62	4.51	4.41	4.30	4.20	4.09	3.98	3.88	3.77	3.66
Upper Bound	5.72	5.61	5.50	5.38	5.27	5.16	5.05	4.94	4.83	4.72	4.61	4.50	4.39	4.28	4.17	4.06	3.95	3.84	3.73



A **Squadron (Sqdrn)** pilot identifies an aircraft issue during flight.

The pilot logs the flight hours and the gripe into **OOMA NALCOMIS** in the **Sqdrn MCC (Maintenance Control Center)**.

Sqdrn MCC assigns their appropriate work center to investigate the gripe.

The gripe requires a replacement component, and the work center removes the bad component and orders an **RFI (ready for issue)** part in **OOMA NALCOMIS**.

A picking ticket prints in **SRS (Supply Response Section)**. **RCU (Requisition Control Unit)** passes the request to **CCS (Component Control Section)** for processing. **MDU (Material Delivery Unit)** picks up the **RFI (ready for issue)** part from **RAM (Repairable Asset Management)** and delivers it **Sqdrn MCC**.

Sqdrn work center picks up the **RFI** from their **MCC** and installs the component. Components listed on the **CRIPL (Consolidated Remain in Place Listing)** (i.e. landing gear) are exempt from the mandatory one-for-one turn in rule and can remain in place until an **RFI** arrives on station

Sqdrn turns in their **NRFI (not ready for issue)** part to **AMSU (Aeronautical Material Screening Unit)** with a copy of their **MAF (maintenance action form)**.

AMSU validates the **MAF** against the **NRFI** part that is turned in. After checking and testing the **NRFI** part against the **ICRL (Individual Component Repair Listing)**, **AMSU** assigns it to an **FRC shop** for repair.

The appropriate **AIMD shop** picks up the **NRFI** part from **AMSU** and puts it in the queue for repair.

Production Control and **MMCO (Maintenance Material Control Officer)** prioritizes the work output for all **AIMD shops** based on the **Priority Groups (PG)** and **Issue Response Times (IRT)** of all MAFs inducted in AIMD.

FRC shop commences work on the **NRFI** part.

AIMD shop determines that an **SRA (Shop Replaceable Assembly)** is needed to repair the part.

If the **SRA** is **not on board**, it is ordered off station with the same priority as the **MAF**, and the **WRA (Weapons Replaceable Assembly)** is taken to the **AWP (Awaiting Parts)** locker.

If the **SRA** is **on board**, **AIMD shop** orders it via **R-SUPPLY** and a picking ticket prints in **SRS**. The **TRU (Tech Research Unit)** validates the request, and **MDU** delivers the part to the shop.

The **SRA** is received on board and delivered to **AWP**. Both the **WRA** and **SRA** are delivered to the **AIMD shop**.

AIMD shop repairs the component part and delivers it to **DCU (Document Control Unit)** for **CRA (Completed Repair Action)**.

DCU determines the disposition of the asset. **DCU** will issue it if an **EXREP (Expeditious Repair)** exists with a request for the same part. Or, **DCU** will send it back to **RAM**.

DCU clears the **CRA** mailbox and a re-stow notice is printed. **RAM** is contacted to pick up the part and re-stow.

All **CRA** transactions in **NALCOMIS** get recorded on the **TIR (Transaction Item Report)** in **S-1**.

Figure 17. Functional Relationship between Squadron, ASD and I-Level (“NAMP,” 2021).

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