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THESIS

SIMULATING CONSUMABLE ORDER FULFILLMENT VIA ADDITIVE MANUFACTURING TECHNOLOGIES

by

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March 2023

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Operational availability of naval aircraft through material readiness is critical to ensuring combat power. Supportability of aircraft is a crucial aspect of readiness, influenced by several factors including access to 9B Cognizance Code (COG) aviation consumable repair parts at various supply echelons. Rapidly evolving additive manufacturing (AM) technologies are transforming supply chain dynamics and the traditional aircraft supportability construct. As of June 2022, there are 595 AM assets within the Navy's inventory—all for research and development purposes. This report simulates 9B COG aviation consumable fulfillment strategies within the U.S. Indo-Pacific sustainment network for a three-year span, inclusive of traditional supply support avenues and a developed set of user-variable capability inputs. Simulated probabilistic demand configurations are modeled from historical trends that exploit a heuristic methodology to assign a "printability" score to each 9B COG requirement, accounting for uncertainty, machine failure rates, and other continuous characteristics of the simulated orders. The results measure simulated lead time across diverse planning horizons in both current and varied operationalized AM sustainment network configurations. This research indicates a measurable lead time reduction of approximately 10% across all 9B order lead times when AM is employed as an order fulfillment source for only 0.5% of orders.

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SIMULATING CONSUMABLE ORDER FULFILLMENT VIA ADDITIVE MANUFACTURING TECHNOLOGIES

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
AEL	allowance equipage list
AM	additive manufacturing
AOR	area of responsibility
APL	allowance parts list
ASTM	American Society for Testing and Materials
BE	build error
BJ	binder jetting
CAD	computer-aided design
CDLP	continuous digital light processing
CM	conventional manufacturing
CSV	comma separated values
COG	cognizance code
DBS	demand-based spares
DDBC	Defense Logistics Agency Distribution Barstow, California
DDDC	Defense Logistics Agency Distribution San Diego, California
DDDK	Defense Logistics Agency Distribution Korea
DDGM	Defense Logistics Agency Distribution Guam
DDJC	Defense Logistics Agency Distribution San Joaquin, California
DDNV	Defense Logistics Agency Distribution Norfolk, Virginia
DDPH	Defense Logistics Agency Distribution Pearl Harbor, Hawaii
DDPW	Defense Logistics Agency Distribution Puget Sound, Washington
DDSP	Defense Logistics Agency Distribution Susquehanna, Pennsylvania
DDYJ	Defense Logistics Agency Distribution Yokosuka, Japan
DLA	Defense Logistics Agency
DLP	digital light processing
DMLS	direct metal laser sintering
DOD	Department of Defense
DOD	drop-on-demand
DON	Department of the Navy

DTO	direct turn over
EBAM	electron beam additive manufacturing
EBM	electron beam melting
FAD	force activity designator
FDM	fused deposition modeling
FSC	federal supply classification
GPC	great power competition
IDE	integrated development environment
IG	inspector general
INDOPACOM	Indo-Pacific Command
IP	intellectual property
IPG	issue priority group
JAMMEX	Joint Additive Manufacturing Model Exchange
JAMWG	Joint Additive Manufacturing Working Group
JTDI	Joint Technical Data Integration
LENS	laser engraving net shape
LOM	laminated object manufacturing
LRT	logistics response time
MB	megabytes
MH-60R	maritime helicopter–60 Romeo
MJF	multi-jet fusion
NAVSUP	Naval Supply Systems Command
NIS	not-in-stock
NPJ	nanoparticle jetting
NSN	national stock number
OEM	original equipment manufacturers
PRC	People's Republic of China
PROJ	project
Q/C	quality check/control
R&D	research & development
RBS	ready-based spares
S&T	science & technology

SC	supply chain
SPSC	spare parts supply chain
SLA	stereolithography
SLS	selective laser sintering
STEM	science, technology, engineering, and mathematics
SYSCOM	systems command
U/I	unit of issue
UC	ultrasonic consolidation
USPACFLT	United States Pacific Fleet
USINDOPACOM	United States Indo-Pacific Command
USA	United States Army
USAF	United States Air Force
USCG	United States Coast Guard
USMC	United States Marine Corps
USN	United States Navy
USSF	United States Space Force
WSS	Weapon Systems Support

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—W—

"Journey before destination. A journey will have pain and failure. It is not only the steps forward that we must accept. It is the stumbles. The trials. The knowledge that we will fail. But if we stop, if we accept the person we are when we fall, the journey ends."

—Dalinar Kholin, from Oathbringer by Brandon Sanderson

EXECUTIVE SUMMARY

This research focuses on the simulation of hypothetical naval aviation consumable spare part supply chains inclusive of additive manufacturing (AM) as a supply source to fulfill orders within the United States Indo-Pacific Command (USINDOPACOM) sustainment network. AM is a rapidly evolving technology that will transform supply chain dynamics; however, it still has many limiting factors for its board employment and replacement of traditional repair part procurement methodology. With the increasing developments in AM technology, implementing AM into more military support constructs will disrupt traditional manufacturing supply chain dynamics and impact contracted spare parts purchase levels. However, the readiness afforded by AM is critical to the increased operational support of warfighters needed in a high-end 21st-century fight. Through the employment of AM within DOD supportability networks, a decreased reliance on contracting actions to procure long lead time repair parts will transpire—a boon to readiness thanks to decreased lead time. From this, two primary objectives for this thesis and research emerge, (1) discover and further develop current tools for classifying the "printability" of individual NSNs, and (2) build a simulation to test assumptions about "printability" ratings based solely on a requisition's continuous characteristics, as well as stress a fictional but possible operational AM fulfillment network. The simulation results yield measurable lead time reductions of approximately 10% across all 9B cognizance code (COG) orders when AM-fulfillment is the source for only 0.5% of orders across a three-year time horizon.

The first research objective seeks to evaluate the potential "printability" of a requirement based upon the characteristics of its specific order, such as the item weight, cube, quantity ordered, project code, Federal Supply Category, unit of issue, and source of supply. A novel printability heuristic scores each order based on these order characteristics and sorts requisitions into groupings of likely highly printable orders through non-printable orders. Figure 1 offers a profile of the most highly printable 9B COG order characteristics evaluated by the printability heuristic.

	Order Characteristic	Values / Codes	Key Insights
1	Federal Supply Class	1560, 1680, 5305, 5310, 5340	Top 5 occuring FSC's: Screws, Airframe Structural Components, Hardware (Access Covers; Bumpers; Casters; Cabinet and Door Hardware; Hinges; Latches), Nuts and Washers, Miscellaneous Aircraft Accessories (Control Assemblies, Actuators,; Ventilators, Relief Tubes; Map Holders, Safety Belts, Harnesses, Electric Windshield Wipers)
2	Cube	0.0169	Average Cube was 0.0169 cubic meters, or 1031 cubic inches. Translating to approximately a 10" x 10" x 10" volume measure
3	Weight	0.467	Average Weight was 0.467 Kg, translating to just over 1 lbs, approximately
4	Unit of Issue	EA	All the most highly printable part orders had a unit of issue of EA
5	Order Quantity	0, 1, 2, 3	Average order quantity was 2.57, so approximately 3 items per order
6	Project Code	AK1, BK0, 706, ZC8, ZK3	Top 5 occuring Project Codes: Partial Mission Capable Support Equipment, Aviation unscheduled repair work stoppage, Not Mission Capabile Supply West Coast, Awaiting Parts for Repair, Engine or major component, Aircraft Flight/Survival Equipment
7	Source of Supply	SMS, NRP	All the most highly printable part orders had contracting as their source of supply. 75% filled by SMS - DLA Aviation, and 25% filled by NRP - NAVSUP WSS
6	Average Lead Time	219	Average order fulfillment lead time for the most highly printable 9B orders, ~219 days
7	NSN	016477464 124075134 014932036	Nomenclature for top three most reordered highly printable parts: 1) FAIRING,WING,AIRCRAFT, 2) UTI RESILIENT MOUNT, 3) SCREW,CLOSE TOLERANCE

Figure 1. Part Profile for Highly Printable 9B COG Orders

The method developed herein samples 3-years' worth of recent repair part data for deployed naval forces within the USINDOPACOM area of responsibility. The data, provided by Commander, U.S. Pacific Fleet (COMPACFLT) N41B Fleet Supply Directorate, is sorted into sample groupings by the heuristic mentioned above and assigns a printability score to the order. These sample groups then provide the necessary input parameters to feed a Monte-Carlo simulation which generates synthetic demand data and models 9B COG order flow. Then these groups align with the second research objective, which endeavors to build a simulation to test assumptions about "printability" ratings based solely on an order's continuous characteristics, then attempt to stress a fictional but possible operational AM fulfillment network.

We then configure the model to evaluate eight different current hypothetical supply chain scenarios inclusive and exclusive of AM capability. The simulation output yields lead time performance metrics across a finite user-specified planning horizon for consideration and analysis to provide insights into the lead time improvements offered by an operationalized AM fulfillment source. This evaluation methodology offers a glimpse into the eventual future of warfighter support afforded by AM.

Results suggest measurable lead time reductions of approximately 10% across all 9B COG orders are achievable when we employ AM as an order fulfillment source. For this finding we assume the existing 81 commercial-quality AM machines currently deployed at Naval facilities globally and onboard Naval ships execute the manufacturing of each order. This reduction presents when only 0.5%, or approximately 2,750 orders, are fulfilled via AM across a 3-year time span. The results point to a potential 14-day reduction in lead time for orders typically contracted that require greater than thirty days to complete.

In the current state supply network and our simulated AM-inclusive supply network, the warfighter customer receives the preponderance of their 9B COG orders in less than ten days. When sampling the most highly printable orders from the source data as simulation input parameters, AM-inclusive networks achieve this 10-day threshold for 95% of all orders over a three-year span. Non-AM equipped networks only meet this threshold for 86% of orders across the same time horizon. These results offer more definitive impacts that AM could have on 9B COG lead time, especially for orders historically filled via contracting and longer lead times. This additional nine percentage points present when scenarios are modeled, including the highly printable longer lead time contracted orders. Leading to the conclusion that the sooner we can operationalize AM to produce safe parts while running in parallel with traditional order fulfillment methodologies, we can see lead time improvements enterprise-wide even while AM-fulfillment only comprises a small fraction of orders.

For future work, this research will be most effective when paired with alternative evaluation tools currently in development which consider more engineering and material factors when evaluating printability. Several points of issue that served as limitations within the simulation model could be areas to refine the model's input parameters. Some of these included modeling machine downtime and AM machine available due to worker shifts and/or off-days into the simulation. Also, including several cost parameters such as engineering design time, raw materials, transportation, and AM operating expenses into the printability heuristic and simulation model would be logical extensions.

I. INTRODUCTION

A. BACKGROUND

Additive manufacturing (AM) is the transformative technology where a user, customer, or warfighter can download schematics, push a button, and print their requirement seemingly from thin air. In July 2022, the USS ESSEX (LHD-2) took delivery of a Xerox liquid metal 3-dimensional (3D) printer, the fastest extrusion-based metal printer. In a recent article in *3D Printing Industry*, the author Kubi Sertoglu explains, “the machine can fabricate aluminum parts up to 10” x 10” in size and will eventually be used [onboard the ship] to print fuel adapters, heat sinks, bleed air valves, housings, valve covers, and more” (Sertoglu 2022). Simply put, an asset like this liquid metal printer accelerates and enhances our warfighting readiness.

The need for this accelerated readiness posture is made clear and apparent from the strategic guidance *Transforming Naval Logistics for Great Power Competition* issued by the Chief of Naval Operations (CNO) in 2021 (p. 2):

> The People’s Republic of China (PRC) and the Russian Federation employ all instruments of their national power to undermine and remake the international system to serve their own interests. China’s and Russia’s revisionist approaches in the maritime environment threaten U.S. interests, undermine alliances and partnerships, and degrade the free and open international order. Moreover, China’s and Russia’s aggressive naval growth and modernization erode U.S. military advantages. Naval logistics is foremost among those eroding advantages.

These emerging threats within the Great Power Competition (GPC) necessitate transformational change throughout every echelon of the naval logistics paradigm. The pressures from our adversaries will be at the highest within the United States Indo-Pacific Command (USINDOPACOM) area of responsibility (AOR), specifically the deployment geozones within this region, as shown in Figure 1. The CNO further outlined that empowering U.S. Forces to prevail in the GPC will occur by delivering “operationally-relevant logistics with respect to materiel and services, location, and timeliness enabled by integrated logistics command and control, assured sea control and power projection, sustainment for distributed operations, and resilience.”

Figure 1. U.S. INDOPACOM Deployed Geozone Ship and Homeport Nodes, including DLA Global Distribution Centers. Source: U.S. PACFLT N41 (2016).

In addition to having persistent, nimble, and fluid naval combat forces, U.S. logistical forces must also retain the same qualities and capabilities as the warfighters they support. Naval logistics can catalyze strategic advantage for the GPC by accelerating the forthcoming evolution of the DOD supply chain by integrating and operationalizing AM.

The U.S. Navy has tested AM technology for over a decade (Nicholls et al. 2019) to address supply shortages. This technology's benefits are disruptive and will completely transform current sustainment networks and supply chains by co-locating repair part production with the end user. Additively manufactured parts are often easier and faster to produce than traditional parts and can be "printed-to-order" with little lead time. This print-to-order capability enhances readiness and gets parts to where needed on short notice for sustainment applications. AM also allows for producing complex shapes and geometries that would be difficult or impossible to produce using traditional methods (Banks et al.

2020). This capability can lead to improved functionality, reduced weight and lower volume, all of which can save costs associated with transportation and storage.

The Xerox liquid metal 3D printer shows tremendous opportunity for broad deployment within the U.S. Navy. The machine employs similar manufacturing processes as fused deposition modeling (FDM) extrusion-based machines, which hobbyists often use due to their shallower learning curve. However, this machine creates production quality metal parts that require minimal post-processing, produced in mere hours—a vast improvement compared to current metal AM technologies. This AM capability is a singular example of the opportunities where AM can lower lead times and expenses in the spare parts supply chain (SPSC).

Conversely, AM is not without its disadvantages. One of the challenges AM poses is the dearth of printing materials, resulting in large machine and material expenses. Additionally, with AM, product design, intellectual property and digital ownership remain complicated issues requiring solutions. The companies that initially designed the materials have intellectual property rights, from the 3D computer-aided design (CAD) models to the test and quality assurance data. However, from a legal perspective, the Navy as a customer of these companies has the intrinsic right to repair its broken equipment (Audette 2022). However, this inherent right to repair comes with risks of intellectual property theft, as legalities are involved in redesigning and reengineering a repair part that a private company initially designed, tested, and built. Any attempts to reverse or reengineer a part from the original manufacturer's technical drawings, blueprints, or 3D models, obtained from the original equipment manufacturers (OEM) but then used for the express purpose of reengineering and printing the item, is a copyright infringement. Under 35 United States Code (U.S.C.) Section 112(f) clearly states that in the case of AM, using a "blueprint produces the patented subject matter and is, therefore, a direct infringement. Printing an object from an altered blueprint may also constitute an infringement if the differences between the original and altered objects are insubstantial." A motivated service member with seasoned maintenance experience and training on operating AM machines and CAD modeling could engage in IP theft unintentionally. Intending to get the job done and fix the weapon system with the tools available, they reengineer a repair parts design via CAD, then print the item. While their efforts are free of malice and endeavored with Naval operational readiness in mind, it does not shield the DOD from liability issues.

Based on our research and results, we assert that four pillars of implementation must be in place for effective adoption and deployment of AM throughout the DOD:

1. The right machines, materials, and support equipment with users trained to operate these AM assets.
2. An IP licensing capture and tracking methodology and process where IP originators of part designs are legally credited and compensated when a DOD user prints a licensed or trademarked part.
3. An integrated approval processes for new printable parts, uncompromising in the engineering, quality testing, and safety standards when approving a part for AM.
4. A cohesive ordering process that interfaces with existing DOD supply systems, enabling a unified effort in supporting the warfighter with conventional process and AM as fulfillment sources.

AM will not supplant conventional manufacturing (CM) broadly within the DOD SPSC's, so refined automated decision logic within ordering systems should balance the readiness requirement with economic viability. For example, sending an order for AM consisting of hundreds of metal washers is not a sound decision, even when readiness is at the forefront. Employing printers that can cost up to $5,000 per day to operate, when considering materials, maintenance, and labor, to produce said order of metal washers likely costing several dollars when made via CM.

Leveraging simulation models capturing the integration of AM into the DOD SPSC construct in a detailed and objective manner to enhance understanding of AM factors that impact readiness is the primary goal of this research. Models solely based upon historical demand tend to evaluate the trade-offs between cost and readiness. Since AM can be a readiness enabler and a cost avoidance tactic, we endeavor to compare various 9B cognizance code (COG) supply chain configurations, inclusive and exclusive of AM, for deployed Naval units within the INDOPACOM AOR.

This research seeks to expand upon the fourth pillar of implementation outlined above. We provide a viewpoint of the problem through a supply-centric aperture, with the intent of gleaning helpful insights into the AM-integrated future-state supply chain. Centrally, results favoring how well forward deployed AM assets might perform will provide a forecasting target encompassing the benefit of these machines. Some assumptions are necessary to model all aspects of the supply system, which Chapter IV covers.

B. RESEARCH QUESTION AND OBJECTIVES

DOD's strategic AM direction, put forth by the Joint Defense Manufacturing Council (2021) is driving towards a decentralized, downstream employment of AM throughout the SPSC, with smaller repair depots and end-users primarily utilizing AM technology to produce critical repair parts. In this research, we imagine and effort to simulate a Naval supply chain where the vast challenges regarding the implementation of AM have solutions, and AM productions sites are sources of supply similar to the role filled present day by DOD global distribution centers. Intellectual property, licensing, test and evaluation data, 3D CAD models, training of personnel, the safety of flight usage…the cavalcade of hurdles and challenges all have been solved and put in place. In this world, when a user places an order for a part, the underlying supply system logic decides if that part is not-in-stock, should that order be considered for printing.

How would simulating high-priority order fulfillment to INDOPACOM deployment geozones via AM look? How would parts and orders be evaluated for printing? How would filling direct turnover orders in a new way (via print-on-demand) positively or negatively impact current global supply chains and order lead times?

1. Key Research Question

How does the employment of a wide range of AM technologies impact the fulfillment of 9B cognizance code (COG) high-priority aviation consumables and affect the lead time for all 9B COG requisitions for deployed forces within the INDOPACOM AOR over a three-year time horizon?

2. Research Objectives

The two primary objectives for this thesis and research:

(1) Discover and further develop current tools for classifying the "printability" of individual national stock numbers (NSNs).

(2) Build a simulation to test assumptions about "printability" ratings based solely on a order's continuous characteristics, then attempt to stress a fictional but possible operational AM fulfillment network.

C. STRUCTURE OF THIS THESIS

The remaining chapters of this thesis are structured as follows: Chapter II examines the existing literature surrounding modeling AM supply chains, evaluating "printability" of a part, and the current supply supportability model. Chapter III targets our first research objecting by examining the data sources and development of the printability heuristic. Chapter IV seeks to address our second research objective by offering a synopsis of the simulation model's design and methods. Chapter V summarizes the findings from several discrete event simulations evaluated under various parameters. Finally, Chapter VI concludes the thesis and offers suggestions for further research and expansions.

II. LITERATURE REVIEW AND CURRENT SUPPORTABILITY MODEL

A. RELATED STUDIES AND RESEARCH

Our first research objective is to discover and further develop current tools for classifying the "printability" of individual NSNs. To achieve this, we develop a printability heuristic formula to aid in classification. From Coppin (2004), a *heuristic equation* defined is a formulation used to approximate the value of a variable. Exploiting heuristic equations is best achieved in situations where the exact value of the variable is unknown or difficult to calculate. Coppin again distills heuristics into the "best approximation given the data available."

1. TYPES OF AM

Citing the work of the American Society for Testing and Materials (ASTM) (2013), Robert Saunders (2020), in his Naval Research Laboratory report *Metamaterials Using Additive Manufacturing Technologies,* outlines the uses for every type of AM based on the ASTM classified seven categories of AM, shown in Table 1.

Regarding precision of AM parts based on print category, NAVAIR Engineering 4.1 evaluates each category based on the thresholds in Table 2. To be classified as a commercial quality printer, the tolerance in Table 2 must be matched or exceeded; else, the print is considered hobbyist-grade.

Table 1. Classification of Additive Manufacturing Processes by ASTM International. Source: ASTM (2013).

CATEGORIES	TECHNOLOGIES	PRINTED "INK"	POWER SOURCE	STRENGTHS / DOWNSIDES
Material Extrusion	Fused Deposition Modeling (FDM)	Thermoplastics, Ceramic slurries, Metal pastes	Thermal Energy	• Inexpensive extrusion machine • Multi-material printing • Limited part resolution • Poor surface finish
	Contour Crafting			
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polyamides /Polymer	High-powered Laser Beam	• High Accuracy and Details • Fully dense parts • High specific strength & stiffness • Powder handling & recycling • Support and anchor structure • Fully dense parts • High specific strength and stiffness
	Direct Metal Laser Sintering (DMLS)	Atomized metal powder (17-4 PH stainless steel, cobalt chromium, titanium Ti6Al-4V), ceramic powder		
	Selective Laser Melting (SLM)			
	Electron Beam Melting (EBM)		Electron Beam	
Vat Photopolymerization	Stereolithography (SLA)	Photopolymer, Ceramics (alumina, zirconia, PZT)	Ultraviolet Laser	• High building speed • Good part resolution • Overcuring, scanned line shape • High cost for supplies and materials
Material Jetting	Polyjet / Inkjet Printing	Photopolymer, Wax	Thermal Energy / Photocuring	• Multi-material printing • High surface finish • Low-strength material
Binder Jetting	Indirect Inkjet Printing (Binder 3DP)	Polymer Powder (Plaster, Resin), Ceramic powder, Metal powder	Thermal Energy	• Full-color objects printing • Require infiltration during post-processing • Wide material selection • High porosites on finished parts
Sheet Lamination	Laminated Object Manufacturing (LOM)	Plastic Film, Metallic Sheet, Ceramic Tape	Laser Beam	• High surface finish • Low material, machine, process cost • Decubing issues
Directed Energy Deposition	Laser Engineered Net Shaping (LENS) Electronic Beam Welding (EBW)	Molten metal powder	Laser Beam	• Repair of damaged / worn parts • Functionally graded material printing • Require post-processing machine

Table 2. Accuracy of AM processes. Source: NAVAIR Engineering 4.1 (2018).

Greatest Precision ↕ Least Precision	Process	Tolerance	Materials
	Material Jetting	Satisfies tolerances of < . 004 in	Polymers
	Vat Photopolymerization		Polymers, Resins
	Powder Bed Fusion		Metals, Polymers
	Binder Jetting		Metals, Polymers, Ceramics
	Sheet Lamination	Satisfies tolerances of < .012 µin	Paper, Metal Foils
	Direct Energy Deposition		Metals
	Material Extrusion		Polymers

Appendix A presents a more comprehensive overview of the seven categories of AM. This thesis asserts that through assessment, these seven types of AM technologies fall into three distinct levels of capability, denoted by the color codes within Table 3. Experts from NAVAIR's Navy Price Fighter Squadron provided documentation showing that as of June 2022, the Navy owned and operated 595 AM assets throughout fleet and shore facilities, all for test and evaluation purposes. Most of these AM assets fall within the Level 1 or 2 categories, producing hobbyist quality prints (Ureta and Kuhn-Hendricks 2022). However, 260 of these assets produce commercial-grade prints, which mimic the characteristics and usability of a conventionally manufactured part. The three capability levels will play a prominent role within the simulation model which we expand upon in Chapter IV of this thesis.

Table 3. Additive Manufacturing Print Level Classification by Category with Number of U.S. Navy Commercial AM Assets. Source: Ernesto Ureta and Stephen Kuhn-Hendricks (2022).

Level	Category	Technology	Materials	Operating Difficulty	Post-Processing Requirements	Print Failure Rate	# of USN Assets
1	Material Extrusion	Fused Deposition Modeling	Thermoplastics, resins, photopolymer, metal pastes, ceramics	LOW	HIGH	MED	*26*
	VAT Photopolymerization	Sterolithography Digital Light Processing Continuous Digital Light Processing					
2	Material Jetting	Polyjet NanoParticle Jetting Drop On Demand	Photopolymer, wax, gypsum, metal powder, ceramics, plastic film, metallic sheet, ceramic tape	MED	MED	LOW	*43*
	Binder Jetting	Binder Jetting					
	Sheet Lamination	Laminated Object Manufacturing Ultrasonic Consolidation					
3	Powder Bed Fusion	Selective Laser Sintering Direct Metal Laser Sintering Multi-Jet Fusion Electron Beam Melting	Micro-miniture mat'l, Molten metals, Metal powder	HIGH	LOW	HIGH	*12*
	Directed Energy Deposition	Laser Engraving Net Shape Electron Beam AM					

2. Modeling AM Supply Chains

The substantive research on AM focuses on the technical elements of production. The abundance of more technology-focused research is natural, given that the first phases of AM research concentrate on process development, technology capabilities, materials experimentation, and optimization of these newly discovered insights. These advancements range from the fabrication of microscopic polymer and advanced materials components (Bazinet 2021) to the development of metal AM technology, which requires exceptionally complicated procedures employing metallic powders, liquid metal, lasers, or electron beams (Saunders 2020). AM technology has rapidly progressed, has become more affordable, and is beginning to disrupt conventional manufacturing supply chains (Gray and Depcik 2020).

The need for research on the widespread deployment of AM is paramount to achieving the DOD strategic objectives in this space. How AM might aid, alter, or even displace existing supply chains are questions needing further exploration. Even so, there persist gaps in research as to impact of AM on supply chain logistics. However, several research papers and initiatives into AM supply chains and demand schedules directly informed this thesis.

Holmstrom et al. (2010) establish several foundational insights with their research involving differing configurations of AM within a SPSC. One example is the potential benefits of improved service and reduced inventory through the distributed deployment of AM assets in the supply chain. However, it is worth noting that in this landmark study, the authors concluded that the best way to use AM "is centralized deployment by original equipment manufacturers (OEMs)" (Holmström et al. 2010, p. 687). This recommendation conflicts with the DOD's strategic AM direction (Joint Defense Manufacturing Council 2021) in Chapter I as a primary driver of this research effort.

From their work on AM SPSCs, the authors Khajavi, Holmstrom, and Partanen (2018) quantitatively examine the practicability of different SPSC configurations with integrated AM as a supply source. Using cost data extracted from a case study, the authors modeled and compared three scenarios for each AM machine technology: a hub and spoke model of machine-to-customer distribution, a broad distribution throughout the SPSC, and lastly, a singular production facility scenario. The result provided insight into the feasibility of different levels of decentralization for AM-enabled SPSCs.

McDermott et al. (2021), and further supported by Doudnikoff (2021), contribute foundational research on how to best model AM capability within both a commercial (McDermott et al.) and military network (Doudinikoff) by applying real-world variable demand characteristics. Each author evaluates various AM-enabled supply chain configurations within their respective commercial or military supply chains via a Monte-Carlo simulation model, employing both "historical demand simulation and intermittent demand forecasting, used in conjunction with a mixed integer linear program to determine optimal network nodal inventory policies" (McDermott et al. 2021, p. 2). First, McDermott et al. demonstrate in their seminal research the first exploration linking realistic spare part demand characterization to AM supply chain design using quantitative modeling. Then paralleling McDermott et al., Doudnikoff presents a similar simulation model of an isolated military sustainment SPSC, leading to more insight into underlying spare part demand patterns within military SPSC.

Moore, McConnell, and Wilson (2018) evaluate the effectiveness of AM inside the supply chain by exploiting a discrete event simulation model for a hypothetical use case involving repair parts for the M109A6 Paladin self-propelled 155 mm howitzer. Using a demand sample from OPERATION IRAQI FREEDOM (OIF), taken from the initial 2003 invasion, the authors develop a sample-path-based forecasting approach for determining repair part demand for several scenarios. Their simulation also uses an envisioned future-state AM facility deployed and integrated into the U.S. Army supply chain (2018). This thesis efforts to do the same within U.S. Navy supply chain. The authors examine the efficacy of AM under diverse circumstances, including layer thickness, build rate, and printer usage. The results indicate that AM might be feasible for delivering fifty-eight different spare parts for the M109A6 Paladin within an expeditionary setting. The authors' discrete-event simulation flow, illustrated in Figure 2, also served as the basis for the demand instantiation phase of this research's simulation model. The authors also involved the generation of synthetic orders for the simulation to evaluate and process (2018).

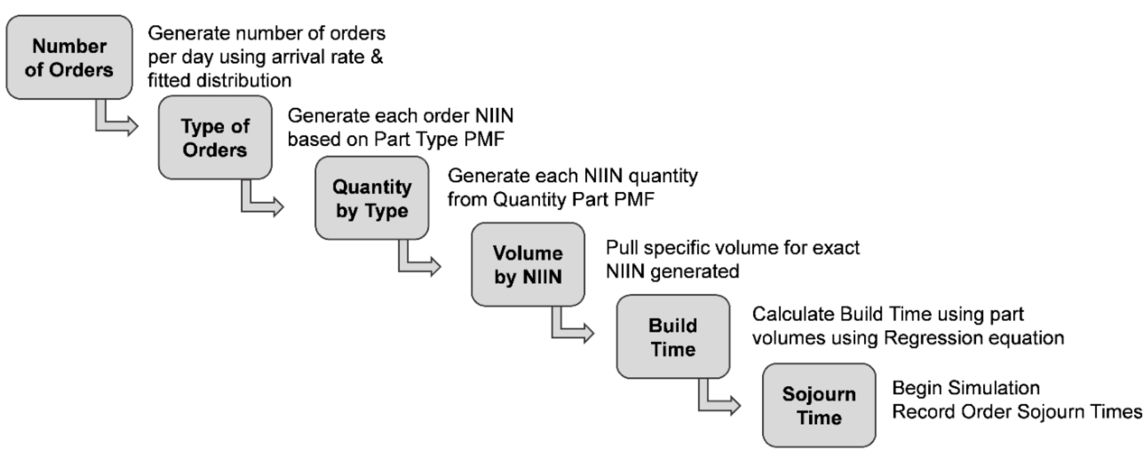

Figure 2. Moore et al. Metal M109A6 Paladin AM simulation flow, generating several orders for each day, consisting of a part type and part quantity. Source: Moore et al. (2018).

3. Evaluating "Printability"

Limited study into quantifying the "printability" of an item exists within the DOD. However, as captured in the article written by King-Sweigart (2021), the most transformative research involves the Naval Supply Systems Command (NAVSUP) Weapon Systems Support (WSS) Navy Price Fighters' AM team. This team, led by Ernesto Ureta, developed a computer-based tool to help determine whether AM or traditional manufacturing is "more cost-effective for complex machinery replacement parts" (King-Sweigart 2021). Some background into the WSS Price Fighters provided by their parent command NAVSUP is the "Price Fighter services engineer cost and price analysis support to the acquisition business management community throughout the Department of the Navy, Department of Defense, and civilian federal agencies. This aligns with DOD's efforts in support of total ownership cost reduction and better buying power efforts." (Naval Supply Systems Command 2021).

From discussions directly with Ureta and his team (2022), their printability tool weighs several factors when evaluating if AM is a good option for a specific part. Considerations such as is the part obsolete, will it require a long time to obtain, can the design be improved upon, what is the build volume, and the cost are all assessed for printability. A key feature not considered in previous evaluation tools and models is the Price Fighter's tool factors engineering and design time as a cost parameter into the model to assess printability.

A key component of this research's simulation model is a function that gauges print failure rates and considers orders identified for AM as potentially not printing successfully the first, second, or third time. In addition, we collect several anecdotal points of data from NPS AM subject matter experts through interviews and discussions. One such point is regarding the Level 3 Xerox Liquid Metal FDM printer, which currently experiences an approximately 33% failure rate (Jones 2022) for first fabrication of an item.

Burrow et al. (2017) observe that advancement in this area has been slow as "current technologies and approaches for qualification and certification are ill-suited for AM components, which are produced unit-by unit in low-volumes with limited confidence in the material, processing history, and component geometry/tolerances (Burrow et al. 2017 p. 9).” During his 2022 presentation to the Spring-22 Advanced Prototyping for the Warfighter cohort, Matt Audette, NPS graduate and current team lead within the Advanced Manufacturing Operations Cell at Marine Corps SYSCOM, presented three methodologies presently undertaken for evaluating printability. These ranged from advanced research leveraging predictive analytics to scrappy and shared collective knowledge pushing AM technology forward. Audette (2022) highlighted another way printability is presently evaluated is through readiness reports reviews, targeting the most in-demand long lead time items. For example, NAVAIR developed and managed the Aviation Management Supply and Readiness Reporting System (AMSRR), which is used to evaluate the material needs of all Naval and Marine Corps aircraft (Pacific Fleet Naval Air Forces 2021). The NAVAIR Systems Engineering, AIR 4.1 team, responsible for AM part approval, evaluate these readiness reports for each requirements potential printability. This review also occurs at the highest echelons of supply and logistics, with the Defense Logistics Agency (DLA) also reviewing the long lead time items, then passing them to the respective services' engineering subject matter experts for a printability assessment.

A separate ongoing initiative is through a partnership between the DOD and the Georgia Tech Manufacturing Institute (GTMI) on a rapid materials screening and property evaluation automated tool (Georgia Tech Manufacturing Institute 2022). From the GTMI AM website, the rapid materials screening and property evaluation tool (2022):

> The goal of the rapid materials screening area is the rapid design, development, and implementation of autonomous workflows for rapid exploration and aggregation of data-driven knowledge systems capable of supporting cost-effective optimized materials-product design for AM multiscale multifunctional components. This technical area focuses on exploiting materials knowledge systems frameworks for rapid mapping of material structure and data-rich process sensing information, establishing testbeds for rapid alloy screening, and supporting materials testing frameworks.

This tool will comb through a vehicle or weapon systems technical data package, evaluate the individual components for printability, and return a listing of likely print candidates. The tool takes input in the form of technical data across the spectrum, such as

3D models, 2D drawings, technical manuals, maintenance manuals, allowance parts lists (APL), or allowance equipage list (AEL), to evaluate and return a prioritized list of printability candidates out of all the individual parts contained within that weapon system. This listing presents recommendations based on material, makeup, size, and print complexity of the most highly printable parts of that weapons system. Cost is also evaluated as part of the tool, comparing the cost to purchase a repair part versus an estimate of the print cost with considerations for raw materials and AM machine operating costs. This automated software tool is presently showing the most promise in future printability evaluation. Printability of components on a new weapon system procurement will likely soon be a tool in programmatic awarding and evaluation of defense spending. For example, the evaluation tool could consider the technical data from multiple contractor proposals for a newly planned weapon system procurement and return the percentage of printable parts on each bid. This level of detailed information provides insights into life cycle maintenance costs by estimating potential future costs based on past or similar systems. These tools will provide more flexibility across the DOD supply chain.

B. CURRENT US NAVY SUPPORTABILITY MODEL

As the CNO (2021) highlighted, the modalities presently employed by Naval logisticians contribute to eroding advantages against adversaries.

> Over the past several decades, naval logistics has been optimized for a permissive maritime environment against non-peer adversaries–in short, for day-to-day peacetime operations only. The resultant “hub-and-spoke” system–reliant on fixed, land-based logistics hubs with spokes comprised of a smaller Combat Logistics Force, supplemented by commercial carriers for “just-in-time” delivery–is inadequate to sustain a high-end maritime conflict. Moreover, a decided, decades-long focus on cost efficiency has led to an accumulation of risk with regard to combat-effective logistics.

The CNO’s words further highlight the operational necessity of transforming SPSCs past their current peace-time configurations. Nevertheless, to illuminate paths and opportunities to evolve and grow the SPSC with AM, understanding the processes and responses given by the current-state SPSC is of primary concern.

1. Operational Forces Supply Procedures

We present the following section detailing current-state supply procedures written through the authors' lens of fifteen years as a U.S. Navy Supply Corps officer. While there are hundreds of nuanced instances divergent from these foundational processes, often arising in the fluid realm of operational supply and logistics, listing and elaborating on all these situations is beyond the focus of this research. Instead, this is a broad and generalized overview of the current-state backbone processes enabled by the global DOD supply system. The following steps, outlined in the NAVSUP P-485 Operational Forces Supply Procedures, as well as the Naval Aviation Maintenance Program Instruction 4790.2D, are used to detail the process of procuring a part through the Navy supply system:

(1) A maintenance technician identifies the part, generally via the parts NSN or part number.

(2) The technician develops a work request and orders parts to complete the identified maintenance action. A Logistics Specialist then screens the parts requirements. If the part is available and ready-for-issue within the local inventory, the part is picked and issued to the customer.

(3) If the part is not in stock, the request goes to a Navy Supply Fleet Logistics Center (NAVSUP FLC) or DLA Distribution center for action.

(4) If NAVSUP FLC or a DLA Distribution Center cannot fill the requirement, the parts' respective item manager (IM) fields the order, and undertakes a contracting action for the requirement. Contracted procurement via the IM can range from several days to years for zero-demand obsolete items. Therefore, an active contract for the ordered part or a new contracting action needing to occur serves as a basis for lead times. When IMs must solicit bids from conventional civilian manufacturing companies to produce the requirement, lead time for the requirement increases reflective of this contracted procurement action.

(5) All the while, the requesting operational supply department tracks the status and anticipated delivery date and provides updates to the customer as required. The requesting customer receives their requirement once its ultimately acquired from the CM source, with

local FLC supply or DLA distribution center as an intermediate processing location arranging for final delivery to the ordering command's supply department. (NAVSUP 2015). See Figure 3 for an illustration of the supply procedures.

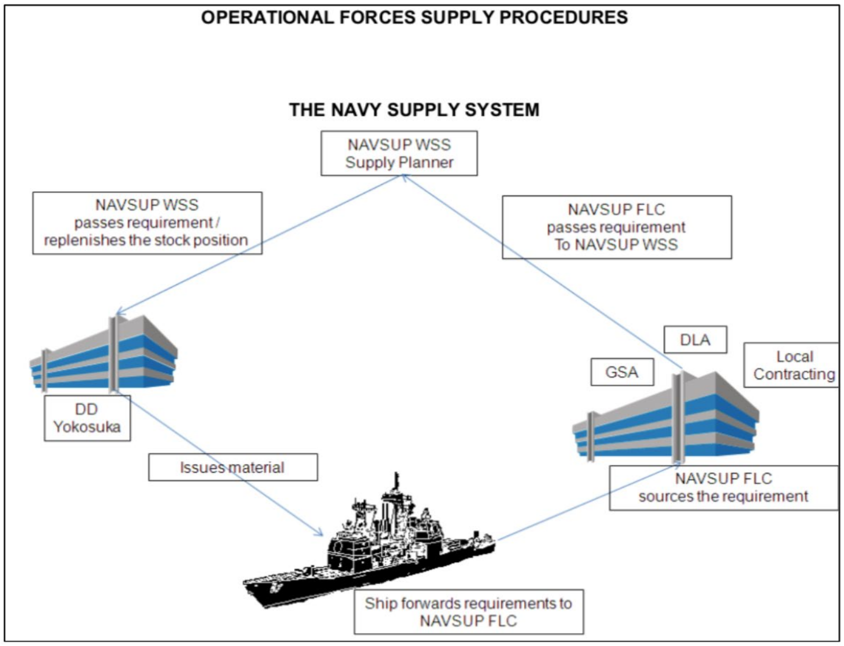

Figure 3. NAVSUP Operational Forces Supply Cycle.
Source: NAVSUP (2015).

2. Logistics Response Time

An awareness of the considerations affecting logistics response time (LRT) aids in developing processes and policy leading toward consistent reductions in LRT, thereby supporting improved operational readiness. LRT is the critical metric to measure the effectiveness and responsiveness of the global DOD supply system (Chief of Naval Operations 2022). Tracking LRT begins the order date and concludes when the ordering command's supply department posts receipt of the order in the automated supply system. Herein the remainder of this research, LRT is described simply as *lead time.*

III. PRINTABILITY HEURISTIC FUNCTION

Our first research goal seeks to discover and further develop current tools for classifying the "printability" of individual NSNs. To achieve this goal we develop an easy-to-calculate heuristic formula to approximate the printability of a part from a supply-centric perspective. We developed this formula as a first pass additive function that assesses the attractiveness of employing AM to fulfill the repair parts requirements, based on the order characteristics we received.

Our printability function is based on seven scores, one from each of the following categories: *Federal Supply Class, Cube, Weight, Unit of Issue, Order Quantity, Project Code* and *Source of Supply*. In each category, we determine a score for that category based on data we pull from each order. These individual categorical scores feed the printability function, which takes the form of a simple additive function that sums the seven categorical values. The formulation is shown in Equation (1).

$$Ps = \sum_{i=1}^{7} v_i \qquad (1)$$

Ps represents printability score where v_i reflects the categorical variables. The remainder of the chapter will describe in detail how each categories scores are determined. We discuss the reasoning behind each score and Table 4 illustrates an overview of each of the categories possible scores. Within the chapter we elaborate each category with short form examples, however Appendices C through F provides the entirety of the evaluated source data for each categorical variable for review as required.

A. PRINTABILITY FORMULATION

We derive a composite heuristic formula to evaluate an order's printability potential based on its continuous characteristics. It evaluates and assigns a possible thirty-seven-point numerical score based on the individual order continuous characteristics. The heuristic is a function of the sum of the seven categorical variables, outlined in Table 4.

Table 4. Composite Printability Heuristic Formulation Categories Overview

	Order Characteristic	Function Name	Numerical Score Values Awarded	Composite Heuristic Parameters when Sampling Source Data	Awarded Score Output Column Name
1	Federal Supply Class	assign_ print_ score	0, 1, 3, 6	If Column "PRINTABLE_FSC" is "**YES**" then award score = **6** If Column "PRINTABLE_FSC" is "**MAYBE**" then award score = **3** If Column "PRINTABLE_FSC" is "**NO**" then award score = **1** If Column "PRINTABLE_FSC" is "(**BLANK**)" then award score = **0**	*FSC_print_ score*
2	Cube	assign_ cube_ score	0, 1, 3, 6	If Column "DSS_CUBE" is < = **0.208992**, then award score = **6** If Column "DSS_CUBE" is **> 0.208992**, then award score = **3** If Column "DSS_CUBE" is **> 1**, then award score = **1** If Column "DSS_CUBE" is **> = 2**, then award score = **0**	*Cube_print_ score*
3	Weight	assign_ weight_ score	0, 1, 3, 6	If Column "DSS_WEIGHT" is < = **1,** then award score = **6** If Column "DSS_ WEIGHT" is **> 1** but **< = 4,** then award score = **3** If Column "DSS_ WEIGHT" is **> 4** but **< = 25,** then award score = **1** If Column "DSS_ WEIGHT" is **> 25**, then award score = **0**	*Weight_ print_ score*
4	Unit of Issue	assign_ UI_ score	0, 2, 4	If Column "UI" is "**EA, PR, SK, SP, SL, OZ, MM, CM, IN, LG, FV, BO**," then award score = **4** If Column "UI" is "**LB, KG, DZ, KT, CN, BR, AT, BG, BD, CY, FT, PZ, TO**" then award score = **2** If Column "UI" is "(**ELSE**)" then award score = **0**	*UI_print_ score*
5	Order Quantity	assign_ qty_ score	0, 1, 2, 3	If Column "QUANTITY" is < = **10,** then award score = **3** If Column "QUANTITY" is **> 10** but **< = 20,** then award score = **2** If Column "QUANTITY" is **> 20** but **< = 100,** then award score = **1** If Column "QUANTITY" is **> 100,** then award score = **0**	*Qty_print_ score*
6	Project Code	assign_ project_ score	0, 1, 3, 6	If Column "PROJECT_PRINTABLE" is "**YES**" then award score = **6** If Column "PROJECT_PRINTABLE" is "**MAYBE**," then award score = **3** If Column "PROJECT_PRINTABLE" is "**NO**," then award score = 0	*Project_ print_ score*
7	Source of Supply	assign_ source_ score	1, 3	If Column "CONTRACT_FILLED" is "**YES**" then award score = **3** If Column "CONTRACT_FILLED" is "**NO**" then award score = **1**	*Source_ print_score*

A *heuristic evaluation function* is a function that approximates a value that cannot necessarily be calculated—in this case, we are approximating the printability score for a part based on simple categorical scores for each characteristic we have selected.

The heuristic function calculates the approximate printability score for any order, which is then used to create distinct groupings of orders clustered by total printability score from the sampled data. The average lead time, number of orders and average quantity per order of each sample grouping serve as the key input parameters to instantiate the four distinct demand schedules in play for each simulation scenario, covered within Chapter IV.

Of note from the initial sampling, the group with the highest printability scores, insinuating attractive print candidates, was exclusively comprised of orders filled via contracting as their source of supply. This initial finding offered assurances that the function grouped and identified potential printability with a degree of accuracy. Therefore, with confidence that the heuristic evaluates the orders and categorizes them in a reasonable way, we perform a sensitivity analysis of this heuristic scoring and sampling methodology with the results outlined in Chapter IV, Section B, Paragraph 5.

B. FUNCTION VARIABLE DESCRIPTIONS

1. Federal Supply Classification

The Federal Supply Classification (FSC) outlines the various stratums (part types) for the 78 different groups and 645 classes categorizing the universe of supply commodities. More specifically, from the FSC handbook (2003), each class covers a "relatively homogeneous area of commodities, in respect to their physical or performance characteristics" (p.ii), or in "the respect that the items included therein are such as are usually requirements." Appendix D details the complete breakdown of FSC codes and their *YES/NO/MAYBE* printability potential labeling, from which the heuristic draws.

2. Cube

A survey of lab-scale and industrial-scale build volumes for the most common polymer technologies indicates they are generally comparable in size to metal powder bed forming (FBM) printers with build volume dimensions as follows (Schmelzle 2018a):

- Lengths of 1.5 to 36 in, with most falling between 4 and 14 in
- Widths of 1 to 26 in, with most between 4 and 14 in
- Heights of 5 to 37 in, with most between 16 and 16 in

Using these measures as a framework for the *Cube* scoring parameters, four scoring groups are created, based on a parts cube value and favoring parts and orders with lower cube. A complete listing of the current U.S. Navy AM assets and their build plate dimensions is found within Appendix F.

3. Weight

When sampling the source data, the mean weight value was 4.055 lbs per item ordered. Plotting the data as a normal distribution, the standard deviations to the left and right of the mean became the heuristic scoring groups for *Weight*. The heuristic favors lighter and smaller values for weight, as lower weight is directly correlated to lower AM print times. Also, the cost of raw materials becomes a consideration with weight. Advanced materials utilized in Level 1 printers, like POLYMIDE PA6-CF carbon fiber-infused Nylon filament, cost around $100 per kilogram (Digikey Electronics 2022). Higher-level AM SLS machines utilize Ti-6Al-4V titanium-based metal powder to fabricate items. This powder has a bulk cost range of $275–$429 per kilogram (MSE Supplies LLC 2022). While cost is not a variable considered in this research, we assume controls would be in place in a Print-on-Demand environment preventing heavy items made from expensive materials when the items made via CM would be markedly less.

4. Unit of Issue

In its storage connotation, unit of issue (U/I) represents each number, dozen, gallon, pair, pound, ream, set, and yard, for example, and refers to the amount of an item present in one unit. The heuristic naturally favors U/Is that are representative of smaller quantities or measures, such as EACH (EA), PAIR (PR), or INCH (IN). It is easier to produce a singular item via AM than an item that requires one hundred copies, as that item has a U/I of HUNDRED (HD). Therefore, counter to the predilection for U/Is representative of smaller quantities, U/Is intrinsically representative of larger quantities or measures, such as TON (TN), YARD (YD), THOUSAND (MX), or HUNDRED (HD), are unfavorable from a printability perspective. A full detailing of the long-form names and descriptions of all U/I's appearing in source data is found in Appendix E.

5. Order Quantity

When sampling the source data, the mean value for *Quantity* was 10.45 units. Therefore, when plotting the data as a normal distribution, the standard deviations to the left and right of the mean became the heuristic scoring groups for *Quantity*. Paralleling the other variables, the heuristic favors orders with a quantity less than 11.

6. Project Code

Since we scope this research towards evaluating 9B COG aviation consumable orders for printability, all project codes pertaining to Naval aviation, aviation maintenance, airframe weapons systems and support, or Carrier Strike Group (CSG) flight operations are favored. A full detailing of the long-form names and descriptions of all project codes appearing in source data and the classifications of each is available as part of Appendix C.

7. Source of Supply

The *Source of Supply* column directly evaluates the characteristics of the orders with the longest lead times. Orders sent for contracting typically take over 180 days to fulfill, and this variable helps identify contracted items that could then be strong candidates for AM. The heuristic favors orders with "SMS" or "NRP" as the source of supply, indicating contracting action as these orders source.

C. FUNCTION VARIABLE DATA SOURCES

1. Joint Technical Data Integration on AM

To review and sample the source repository, the Joint Technical Data Integration (JTDI) tool establishes the type of items and their associated continuous characteristics approved for AM present day. In addition, the JDTI provides the technical information surrounding the number of parts approved for AM by the process owners at NAVAIR. From this tool we synthesize insight-driven baselines for the establishment of our printability heuristic evaluation parameters. The JDTI provides insight into the characteristics of currently approved AM parts, critical for our derivation of sampling groups. Figure 9 shows the JDTI "Greenbox" list of AM qualified parts.

NAVAIR AM QUALIFIED PARTS LIST (QPL) - GREEN Thursday, August 11, 2022

NAVAIR HAS APPROVED THE ITEMS ON THE NAVAIR AM QPL - GREEN BOX FOR AM MANUFACTURE.
AM QPL ITEMS IN THE GREEN BOX CATEGORY HAVE NO AIRWORTHINESS OR SAFETY IMPLICATIONS AND ARE APPROVED FOR FLEET MANUFACTURE. INSTALLATION OF AM PARTS ON AIRCRAFT MUST BE IN COMPLIANCE WITH CNAF POLICY.

1. AM QPL GREEN BOX CATEGORY ITEMS MUST BE PRINTED USING A NAVAIR APPROVED INTERIM OR FINAL AM TDP IN ACCORDANCE WITH CNAF POLICY. LATEST CNAF POLICY IS ATTACHED TO THIS DOCUMENT.

2. AM TECHNICAL DATA PACKAGES (TDPS) WILL BE PROVIDED ON THE AM JTDI SITE AS THEY ARE APPROVED BY NAVAIR. AN AM TDP DEFINES PRINTERS, PRINTER SETTINGS, MATERIALS, QUALITY ASSURANCE, AND ASSEMBLY/INSTALLATION PROCEDURES TO ENSURE FUNCTIONAL PERFORMANCE OF THE PART WHEN PRINTED.

3. FOR URGENT FLEET NEEDS WHERE AN APPROVED INTERIM OR FINAL TDP IS NOT AVAILABLE ACTIVITIES MAY CONTACT NAVAIR AT NAVAIR_AM.FCT@NAVY.MIL FOR SUPPORT. DEVIATIONS FROM AN APPROVED AM TDP MUST BE IN ACCORDANCE WITH CNAF POLICY.

4. NAVAIR GUIDANCE ON PRINTER TYPES, PRINTER SETTINGS, MATERIALS THAT ARE APPROPRIATE FOR AVIATION USE, TROUBLESHOOTING OF PRINTER FAILURES, DRILLING AND TAPPING PLASTICS, ENCLOSURE DESIGNS TO IMPROVE QUALITY, MATERIAL STORAGE, AND SAFETY IS AVAILABLE ON THE AM JTDI SITE AT WWW.JTDI.MIL. PROCESS TO REQUEST ACCESS TO THE AM JTDI SITE IS ATTACHED TO THIS DOCUMENT.

5. MAINTENANCE ACTION FORMS ARE REQUIRED FOR ALL AM ITEMS AND MUST BE IN COMPLIANCE WITH CNAF POLICY AND COMNAVAIRFORINST 4790.2C OR LATEST VERSION.

6. ASSISTANCE AND SUPPORT CAN BE REQUESTED BY EMAILING THE NAVAIR AM TEAM AT navair_am.fct@navy.mil

Top Level Process Steps	PMA COORDINATION		TDP IN WORK								TDP COMPLETE		
Detail Process Steps	Priority Assigned	Supply Plan	Requirements (1)	Model (2)	Prototype (3)	Test/Fit Check (4)	Prelim Review (5)	Develop TDP (6)	ICL Check (7)	Leader Review (8)	Interim TDP Complete	Final Review (9)	Final TDP Complete
DETAIL STEPS WHERE ADDITIONAL INFO OR SUPPORT MAY BE NEEDED	JUSTIFICATION FOR PRIORITY 1	PRODUCTION PLAN FOR QUANTITIES OVER 100	SPECIAL MATERIAL (E.G. ESD, HIGH TEMP)	3D MODELS FROM REQUESTOR	NON-AM ASSEMBLY PARTS (E.G. SCREWS)	FIT CHECK BY REQUESTER	FEEDBACK ON FIT CHECK	NA	NA	NA	REQUESTER VALIDATION	NA	REQUESTER VALIDATION

DETAIL PROCESS STEPS WILL BE FLAGGED WHEN TIME AT A STEP EXCEEDS 30 DAYS

AM TECHNICAL DATA PACKAGES ARE PDF FILES WITH EMBEDDED ATTACHMENTS THAT ARE ACCESSED BY ENABLING JAVASCRIPT AND SELECTING THE PAPERCLIP ICON ON THE LEFT HAND MENU BAR. USERS OF ADOBE ACROBAT READER SHOULD GO TO THE 'VIEW MENU' AND SELECT 'SHOW/HIDE->NAVIGATION PANES-> ATTACHMENTS'. DRAWING NOTES ON ALL TDPS MUST BE FOLLOWED.

REQ ID	PMA	T/M/S	Nomenclature	Part Description	AM_PART_NUMBER	AM PDDS Number	Request Org	PRI	Date Classified	Top Level Status	Top Lev Date
3	202	AIRCREW	NA	Hydrocarbon Detector	3597AS156-4-AM		CNATRA	PRI 1	6/24/2017	TDP COMPLETE	7/3/2017
387	202	AIRCREW	THUMBREST	Rescue Radio Thumbrest	4212AS0120-1-AM, 4866113-485-1-AM	4212AS0120	PMA	PRI 3	12/10/2018	TDP COMPLETE	12/10/2018
377	207	C-130	SPACER	Lumbar Support Spacer, Seat	4212AS0181-1-AM	4212AS0181	MALS-11	PRI 1	9/14/2018	TDP COMPLETE	10/12/2018
667	207	PSE C-130	CAP, OXYGEN PANEL MOUNT	JOB AID - Oxygen Panel Mount Cap	4227AS0128-AM	4227AS0128	MALS-12	PRI 2	11/25/2019	TDP COMPLETE	9/17/2020
749	207	PSE C-130	BANDOLIER, FLARE (REVISION)	JOB AID - Flare Bandolier TEMPLATE	4227AS0105-1-AM		MALS-12	PRI 2	9/30/2020	TDP COMPLETE	5/10/2021
761	209	ACE	Electrical Binding Post	Audio input ground terminal spacer for test set			MALS-36	PRI 2	3/10/2021	TDP COMPLETE	5/12/2021
772	209	MH-53E	Compass Controller Knob	Pilot/copilot Compass controller			PMA	PRI 3	2/3/2022	TDP IN WORK	2/3/2022
875	209	ACE	W7 Back Shell	Back shell for cable assembly			FRC-MA	PRI 2	5/12/2022	TDP IN WORK	5/12/2022
664	226	PSE F-5	COVER, POWER UNIT	J85-21 VEN POWER UNIT shipping cap	4212AS0175-1-AM, 2488994-AM	4212AS0175	PMA	PRI 3	6/20/2019	TDP COMPLETE	7/6/2020
677	257	PSE AV-8B	COVER, BEARING	JOB AID- Stab Bearing Cover			MALS-14	PRI 2	7/31/2019	TDP COMPLETE	7/23/2019
742	257	AV-8B	Plug/Cover	Plug for AV-8B	4212AS0309-0-AM		MALS-13	PRI 2	5/28/2020	TDP COMPLETE	8/5/2020

Figure 4. Example "Green Box" Qualified Parts List Report NAVAIR AM August 2022. Source: AM JTDI Homepage NAVAIR AM Group (2022).

2. Birdtrack

We source the initial data from Commander, U.S. Pacific Fleet (COMPACFLT) N41B fleet supply directorate, who gather the requested transaction information with their requisition and asset visibility tool *Birdtrack* (Bui 2022). Aside from descriptive data about an individual requisition, such as document number, NSN, and order quantity, Omura (2005) highlights *Birdtrack's* ability to track average customer wait times for replacement parts, measured delivery times, and yields throughout each point in the supply chain. These features were particularly beneficial to our research, as the raw data supplied a window into the circles of activity relating to each transaction. For example, *Birdtrack* allows for the review of each order's supply source, such as NAVSUP weapon systems support (WSS) contracting or a Defense Logistics Agency global distribution center. *Birdtrack* served as the basis for all subsequent database merges, and Table 5 provides an overview of each column's initial column headers and data type. *Birdtrack* provided all the source data required for the function to evaluate the categories *Unit of Issue, Order Quantity* and *Source of Supply*.

Table 5. Initial Source Data Headings—5 years of USN Transaction Data, USINDOPACOM Geozones. Source: Bui (2022).

```
Data columns (total 29 columns):
 #   Column                        Dtype
---  ------                        --------------
 0   Geozone Ordered Description  object
 1   Document Number               object
 2   DoDAAC                        object
 3   Series                        object
 4   NIIN                          object
 5   FSC                           object
 6   Quantity                      float64
 7   UI                            object
 8   Cog                           object
 9   Ordered Date                  object
 10  Entered Date                  object
 11  Issued Date                   object
 12  Shipped Date                  object
 13  Received Date                 object
 14  Source_of_Supply              object
 15  Pricd 01                      int64
 16  Ipg 01                        int64
 17  Geozone Ordered               int64
 18  Geozone Received              object
 19  Is Cancelled                  int64
 20  Is Complete BO                int64
 21  Is Pending BO                 int64
 22  Is Reorder                    int64
 23  Project Code                  object
 24  Required Delivery Date        object
 25  Supp Addr                     object
 26  Fund Code                     object
 27  ADVICE CODE                   object
 28  Est Ship Date                 object
dtypes: float64(1), int64(7), object(21)
```

3. Federal Supply Classification

We build a database of the 340 Federal Supply Classification (FSC) codes appearing in the source data to merge each FSC code's common language description into the source data. The categorical nomenclature is valuable for rapidly evaluating an order separated into printability groups by the heuristic with a commonsense check. Table 6 displays several lines of the FSC database.

Table 6. FSC Data frame with Column Headings "FSC_label," "FSC_Print," "CATEGORYdesc." Source: Department of the Army (2003).

	FSC_label	FSC_Print	CATEGORYdesc
0	0	NO	NaN
1	98	NO	NaN
2	1005	NO	Guns, through 30mm
3	1010	NO	Guns, over 30mm up to 75mm Includes Breech Mec...
4	1015	NO	Guns, 75mm through 125mm Includes Breech Mecha...

Each `FSC_label` is subjectively evaluated based on the primary materials, characteristics, and end-use of the individual items within an FSC category. If an entire item or assembly represented by the FSC cannot be made entirely via AM, we assign a label of *NO* in the `FSC_Print` column. In other words, an item may have multiple sub-assemblies or is an FSC code representing oils and lubricants, medical supplies, or clothing and is therefore non-printables. Conversely, suppose an FSC represents a category of items all containing a singular material, all metal for example, and matching several characteristics of currently AM-produced items from the JDTI database. For this occurrence, the `FSC_Print` column populates with the label *YES*. Lastly, as the primary author's expertise is outside of the fields of systems engineering or material science, if an FSC contained several classes that would meet the criteria for a *YES* label but also encompasses classes matching the criteria for a *NO* label, a label of *MAYBE* is then awarded in the `FSC_Print` column. Again, the primary author's expertise is not in material science or engineering. However, multiple teams of experts at service level system commands, such as the NAVAIR AM Engineering and Navy Price Fighter Squadron teams, are undertaking ongoing initiatives to evaluate an item's printability based on its material compositions and geometry. While desirable, integrating this level of fidelity into the model was outside the scope of this research. Therefore, we conclude while a label of *MAYBE* is a subjective assignment, this remains valid and indicates a substantial opportunity for future research.

The Federal Supply Classification (FSC) database is necessary in expanding upon the numeric FSC codes in the source data. An FSC code is "a commodity classification designed to serve the functions of supply and is sufficiently comprehensive in scope to permit the classification of all items of personal property" (Department of the Army 2003). An excerpt from the FSC handbook is shown in Figure 6.

GROUP 51
Hand Tools

5110 Hand Tools, Edged, Nonpowered
Includes Chisels; Files; Pipe Cutters; Rasps; Saws; Screw Plates; Axes; Hatchets; Machetes.

5120 Hand Tools, Nonedged, Nonpowered
Includes Hammers; Picks; Pliers, except pliers for cutting only; Screwdrivers; Shovels; Construction Rakes, Forks and Hoes; Jacks, including Contractors' Jacks; Wrecking Bars; Glue Pots; Blowtorches.
Excludes Craftsman's Measuring Tools; Gardening Rakes, Forks, Hoes, and other Garden Tools.

5130 Hand Tools, Power Driven
Includes Drills; Riveters; Portable Electric Saws; Pneumatic Tools; Abrasive Wheels, Cones, and other Abrasive Attachments for use only on Hand Held Power Tools.

5133 Drill Bits, Counterbores, and Countersinks: Hand and Machine

5136 Taps, Dies, and Collets; Hand and Machine
Excludes Punching, Stamping, and Marking Dies.

5140 Tool and Hardware Boxes

5180 Sets, Kits, and Outfits of Hand Tools
Note-This class includes sets, kits and outfits consisting of several different items classifiable either in a single class or in several classes. Excluded from this class are sets, kits and outfits consisting of variations (such as size or color) of an item. Classify these items in the same class as the individual item.

Figure 5. Example of Item Grouping 51 from the FSC Handbook, with several Classes referring to differing Hand Tools. Source: Department of the Army (2003).

4. Defense Logistics Agency Public Logistics Data

We access PUB LOG to capture data on each item's weight and cube value. From DLA's public supply data website, PUB LOG delivers publicly releasable logistics information. PUB LOG is a "Logistics Information Services product intended for use by public entities requiring National Stock Number (NSN) information and other cataloging information, including Federal Supply Classification (FSC) data and Commercial and Government Entity (CAGE) codes" (Defense Logistics Agency 2022).

From the Military Standardized Instruction 129R, the characteristic "*Cube*" is the total volume of the package expressed in cubic meters or cubic feet, following the ANSI X12.3 standard (Defense Logistics Agency 2014). From the same reference, the characteristic "*Weight"* is expressed as a one to nine-character numerical value, allows the use of a decimal point, and is assumed to be pounds unless qualified by a different unit of measure, as defined by the two-character ANSI X12.3 Package Level data code (Defense Logistics Agency 2014).

We derive the `DSS_WEIGHT` and `DSS_CUBE,` as well as the `Common_Name` and `Item_Name` fields from the PUB LOG federal supply database. `Common_Name` and `Item_Name` serve as a quick sanity check when viewing the heuristic classifier's output data. We create a *WeightnCube* database containing over 21 million records of all NSN supported U.S. Navy parts. We then scope the *WeightnCube* database to just the records containing COG codes in the source data and produce a more manageable eight million individual record database. We then merge the cleaned source data with the database based on the matching NIIN values in both the source data and *WeightnCube*. Table 8 shows sample headings of the merged *WeightnCube* database.

Table 7. PUBLOG Data frame with Column Headings "NIIN," "DSS_CUBE," "DSS_WEIGHT," "ITEM_NAME," "COMMON_NAME." Source: Defense Logistics Agency (2022).

	NIIN	DSS_CUBE	DSS_WEIGHT	ITEM_NAME	COMMON_NAME
0	006016894	0.058593	0.3500	SHIELD,FLIGHT DECK CREWMAN'S HELMET	NaN
34	006016904	0.055501	0.2316	SHIELD,FLIGHT DECK CREWMAN'S HELMET	NaN
82	006104172	0.097656	0.3600	SHIELD,FLIGHT DECK CREWMAN'S HELMET	NaN
124	006040263	0.111111	0.3600	SHIELD,FLIGHT DECK CREWMAN'S HELMET	NaN
154	006016939	0.039351	0.1320	SHIELD,FLIGHT DECK CREWMAN'S HELMET	NaN
...	...	...	...	...	...
21343011	002847134	0.000831	0.0050	FUSE,CARTRIDGE	NaN
21343063	009198121	0.000284	0.0100	FUSE,CARTRIDGE	NaN
21344058	001781456	0.004861	0.0500	NaN	NaN
21344151	000625866	0.212673	7.0000	CORROSION PREVENTIVE COMPOUND	NaN
21344161	002289258	0.010850	1.0000	BAR,METAL	NaN

After merging data and removing duplicates, 5,584 records had missing values for `DSS_WEIGHT` and/or `DSS_CUBE`. Given the limited access to live supply systems data, we create dummy weight and cube variables for the missing records by drawing from the existing distribution of approximately 1 million records containing weight and cube values, then assigning a dummy weight and cube based on a normal distribution.

5. Project Code

We build a database of the 307 project codes appearing in the source data as preparation as a heuristic input. The assignment structure for column `PRINTPROJ` parallels the assignment logic for the `FSC_Print` column. To assist with selecting aviation-related items, only `PROJECT_CODE` relating to aviation, aviation support equipment, or aircraft carrier flight operations are awarded the label of *YES* or *MAYBE* within the `PRINTPROJ` column. We assign a *NO* label if the project remarks fall outside the scope of this research on Naval aviation, regardless of any printability intuitively implied by the project code remarks. Table 10 shows several `PROJECT_CODE` examples from the generated database.

Table 8. Project Code Data frame with Column Headings "PROJECT_CODE," "REMARKS," "PRINTPROJ." Source: Naval Supply Systems Command (2015).

	PROJECT_CODE	REMARKS	PRINTPROJ
302	ZU7	EA-6B POD 1 Level Requirements	MAYBE
303	ZV5	V-22 Weapon System Training and Training Equip...	MAYBE
304	ZV6	High Pri SSN Requirements (ship by traceable m...	NO
305	ZV9	In-flight Refueling System (ARS - Buddy Stores)	MAYBE
306	ZYM	(No Data)	MAYBE

The NAVSUP P-485 Volume II, Appendix 6 delineates many project code definitions. However, project codes have been added to records within the DOD supply enterprise since the last revisions of the respective instruction in 2015, and a handful of project codes appearing less than five instances within the source data, could not be accurately identified. Figure 6 provides an example of commonly occurring project codes assigned to orders relating to aviation maintenance.

Project Code	Project Title
BK0	Partial Mission Capable Support Equipment (SE). SE is inoperative but adequate workaround, redundancy, or local backup is available. If such a condition is projected to impact aircraft support or production capability in the near term and any additional degradation will jeopardize sustained support of O-level maintenance, the condition qualifies for BA reporting.
BK1	Aircraft Intermediate Maintenance Department (AIMD) unscheduled repair of in-use equipment resulting in a work stoppage.
ZC8	For Aircraft Support Used by the Intermediate Maintenance Activity when requisitioning material to stop an "Awaiting Parts" condition on components and aircraft engines undergoing repair.
ZF7	Broad Arrow Requirements for non-Operational Support Equipment or a Test Program Set (TPS) resulting in the immediate loss of authorized onboard intermediate repair capability for aeronautical components or the loss of SE or TPS degrades workload capacity such that the IMA is unable to sustain readiness to the supported activities.
ZQ9	Engine Maintenance Work Stoppage for all Model Aircraft Engines (not assigned for material required for engines being repaired for bare firewalls – see Project Code ZC8)

Figure 6. Example of Five Aviation Maintenance-Related Project Codes, Denoting a repair part order Related to one of these Categorical Projects. Source: NAVSUP P-485 Volume II, Appendix 6 Naval Supply Systems Command (2015).

D. OUTPUT PRINTABILITY SCORE

Our function evaluates each individual order from the prepared source data. We provide a detailed overview of the source dataset, along with the preparation process in Appendix B for reference. From the possible thirty-seven-point printability score, an individual order's score consolidates each into initial sample groups, shown in Table 9. These four initial sample groups are based upon an order being very attractive to print or not being attractive with gradations in between.

Table 9. Initial Sample Groups by Printability Score

Printability Score Range	Printability Percentile
0 - 14	0 - 25%
15 - 18	26 - 50%
19 - 24	51 - 75%
25 - 37	76 - 100%

From here, probability thresholds for each sample group's fulfillment timelines, continuous characteristics, and intensity values for synthetic demand generation from a Poisson distribution, are consolidated from the four sample groups. We then derive four demand schedules serving as Monte-Carlo simulation model inputs, covered in detail in Chapter IV.

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IV. OPERATIONALIZED AM SIMULATION MODEL

Our second research goal is to build a simulation to evaluate assumptions about "printability" ratings based solely on an order's continuous characteristics, then to stress a fictional but possible operational AM fulfillment network. We have developed a Monte-Carlo simulation model that evaluates supply-centric implementation policies for utilizing AM. The model generates synthetic high-priority 9B COG aviation consumable orders over a user-defined day range mirroring real-world demand and requisition behavior within the INDOPACOM AOR. These orders are then evaluated based on each scenario's policies and parameters, set by the user for testing.

A. INPUT ANALYSIS

The specific values chosen for the input parameters depend on the simulation application use case. Figure 7 contains the input parameters for the first simulation execution. Forty trials are performed for all scenarios modeled in this research for each individual demand schedule. One scenario worth of tests includes a total of 160 trials since we sample from four distinct demand schedules to capture the input parameters needed for each simulation scenario. After the 160 trials are complete, the outputs are aggregated, and averaged summary stats prepared. The controlled input parameter `probs` triggers the simulation to model AM as a fulfillment source for the synthetic orders. We simulate the current-state supply system without operationalized AM as an order fulfillment source by adjusting the `probs` input parameter with Zero "0" values for all list items.

	Phase 1									
	Instantiate Orders Per Day				Assign Quantities Per Day			Weights_SameDayClose Percentage		
Iteration	Days	Limit	Last_Day_Limit	pval	quantity_range	majority_range	majority_prob	weights_dictionary	closed	still_open
1	1100	665	15	0.55	[1,100]	[1,5]	0.6875	{1:75,2:15,3:10}	0.2333	0.7667
2	1100	665	15	0.55	[1,100]	[1,5]	0.6875	{1:75,2:15,3:10}	0.2333	0.7667
3	1100	665	15	0.55	[1,100]	[1,5]	0.6875	{1:75,2:15,3:10}	0.2333	0.7667
4	1100	665	15	0.55	[1,100]	[1,5]	0.6875	{1:75,2:15,3:10}	0.2333	0.7667
5	1100	665	15	0.55	[1,100]	[1,5]	0.6875	{1:75,2:15,3:10}	0.2333	0.7667

Phase 2 Print				
Conditions for Print_Probability				
Day_Splits	probs	print_prob	print_list	probs_dict (must be hard coded)
[1,365,730,1095,1460, 2000]	[.04,.9,1.7,2.3,2.5]	[2,5,3]	['print2','print3','print3']	{ 'print1':(.95,[1,2,3]), 'print2':(.85,[1,2,3,4]), 'print3':(2/3,[1,2,3,4,5]) }
[1,365,730,1095,1460, 2000]	[.04,.9,1.7,2.3,2.5]	[2,5,3]	['print2','print3','print3']	{ 'print1':(.95,[1,2,3]), 'print2':(.85,[1,2,3,4]), 'print3':(2/3,[1,2,3,4,5]) }
[1,365,730,1095,1460, 2000]	[.04,.9,1.7,2.3,2.5]	[2,5,3]	['print2','print3','print3']	{ 'print1':(.95,[1,2,3]), 'print2':(.85,[1,2,3,4]), 'print3':(2/3,[1,2,3,4,5]) }
[1,365,730,1095,1460, 2000]	[.04,.9,1.7,2.3,2.5]	[2,5,3]	['print2','print3','print3']	{ 'print1':(.95,[1,2,3]), 'print2':(.85,[1,2,3,4]), 'print3':(2/3,[1,2,3,4,5]) }
[1,365,730,1095,1460, 2000]	[.04,.9,1.7,2.3,2.5]	[2,5,3]	['print2','print3','print3']	{ 'print1':(.95,[1,2,3]), 'print2':(.85,[1,2,3,4]), 'print3':(2/3,[1,2,3,4,5]) }

Phase 3 NonPrint Nodes									
Probabilities for Each Subset of Nonprint Nodes (ensure no spaces)							Splits of NonPrint Nodes (added days)		
non_print_nodes	subset1	prob_1	subset2	prob_2	subset3	prob_3	Split_1	Split_2	Split_3
['DDBC','DDPH','DDDK','DDDC','DDGM','DDJC','DDI	['DDYJ','DDPH','DD	[1,1,2,2,3,3]	['DDDK','DDDC','DD	[1,1,1,2,2,3	['DDBC','DDNV	[2,3,4]	[.01,.99]	[.95,.05]	[.08,.92]
['DDBC','DDPH','DDDK','DDDC','DDGM','DDJC','DDI	['DDYJ','DDPH','DD	[1,1,2,2,3,3]	['DDDK','DDDC','DD	[1,1,1,2,2,3	['DDBC','DDNV	[2,3,4]	[.01,.99]	[.95,.05]	[.08,.92]
['DDBC','DDPH','DDDK','DDDC','DDGM','DDJC','DDI	['DDYJ','DDPH','DD	[1,1,2,2,3,3]	['DDDK','DDDC','DD	[1,1,1,2,2,3	['DDBC','DDNV	[2,3,4]	[.01,.99]	[.95,.05]	[.08,.92]
['DDBC','DDPH','DDDK','DDDC','DDGM','DDJC','DDI	['DDYJ','DDPH','DD	[1,1,2,2,3,3]	['DDDK','DDDC','DD	[1,1,1,2,2,3	['DDBC','DDNV	[2,3,4]	[.01,.99]	[.95,.05]	[.08,.92]
['DDBC','DDPH','DDDK','DDDC','DDGM','DDJC','DDI	['DDYJ','DDPH','DD	[1,1,2,2,3,3]	['DDDK','DDDC','DD	[1,1,1,2,2,3	['DDBC','DDNV	[2,3,4]	[.01,.99]	[.95,.05]	[.08,.92]

Figure 7. Part Group Highly Printable Input Parameters for Operationalized AM Simulation

1. Derivation of Key Input Parameters

This section describes in detail the logic behind heuristically deriving the approval growth rate for new parts for AM, stochastically assigned print times, and print failure rates.

a. New Part Approved for Print Growth Rate (`print_prob`)

As of 2018, the NAVAIR AM group has a robust and holistic process for approving new parts for AM production. This process keeps aircrew and platform safety at the forefront. From the level of detail and approvals, we infer that a new part must pass through several layers of approvals for AM authorization and use on a Naval aircraft. DOD and contractor personnel can access a complete detailing of this process by applying for JDTI access.

Newly approved for AM parts are assigned a safety classification level, highlighted in Table 10. Parts with Level IV safety classifications have many additional layers of testing and engineering scrutiny paid to them to avoid mishap or aircrew safety due to an unreliably printed part. Conversely, a Level I safety part has fewer engineering approval and test requirements; however, all administrative requirements remain the same.

Table 10. Part Classification Levels. Source: Schmelzle (2020).

Classification Level	I	II	III	IV
Part Consequence of Failure	Negligible	Low	Medium	High
Scope/ Limitation Guidance	Parts meet all of the following criteria: 1) No safety consequence 2) No mission performance impact 3) Not Fatigue critical 4) Non Structural 5) No Air worthiness impact 6) Non CAI/CSI 7) No Risk of damage to other equipment or aircraft 8) No risk of injury to personnel	Parts meet all of the following criteria: 1) No safety consequence 2) Acceptable mission performance impact 3) Not Fatigue critical 4) Not an aircraft structural component 5) Not a CAI/CSI	Parts meet all of the following criteria: 1) Acceptable safety consequence 2) Acceptable mission performance impact 3) CAI with acceptable safety impact 4) Not Fatigue Critical Parts *can* be: 1. Structural	No limitation Parts can be: 1. CAI 2. CSI 3. Fatigue Critical 4. (Life Limited)

With safety classifications paramount to new part approvals, when reviewing the June 2022 JDTI approved parts data summary, we note that 97 of the 298 parts submitted for AM approval were rejected due to risks to aircraft/aircrew safety, amounting to approximately 33% of requests. These rejections, but also the 201 approved or provisionally approved parts, lie across the following Naval Type / Model / Series (T/M/S) aircraft and support programs:

- AIRCREW
- E2/C2–E-2 Hawkeye / C-2 Greyhound
- FA18–F/A-18E/F Super Hornet (Also covers EA–18G Growler)
- P8–P-8 Poseidon
- CSE / PSE–Common / Platform support equipment
- F35–F-35 Lightning II
- MH53–MH-53E Sea Dragon
- NONAV TOOL–Custom Maintenance Related Tooling
- S&T–Science and Technology
- T45–T-45 Goshawk
- T6B–T-6B Texan II
- WEAPS–Aircraft Weapon Systems

Of the approved 201 parts, 27 are fabricated via metal or multi-material AM, representing 14% of records. These would classify as the more advanced Level 2 and 3 print candidates. The remaining 174 items are advanced polymers, indicating Level 1 or 2 print candidates. Lastly, of the 298 total requests, 184 parts are non-NSN supported and were reverse engineered for AM, equating to approximately 91% of records.

The rating of new parts for AM approval is highly subjective at this time, with the fully realized approval process producing new candidates for only the past two years as of the writing of this thesis. For this model, we extrapolate an ideal state of 450 new parts approved for printing per year from available data sources. This rate assumes that 3D models and print GCODE data are already available. Therefore, utilizing the prescribed administrative approval estimations from the NAVAIR AM Standard Work Packages and instructions, shown in Table 11, an approximately eight-day administrate approval process per part emerges. This equates to roughly 30 parts per engineer per year, assuming only one part approval at a time, with a 242 working day year. Lastly, inferring a team of fifteen engineers working on these part approvals would roughly equate to 450 new part approvals annually.

Table 11. NAVAIR AM Part Classification Metrics. Source: Alan and Schmelzle (2020).

Work Step	Calendar Time (Days)	Labor Hours
7.1 Customer requests	N/A	1
7.2 Logistics Information Gathering	1	2
7.3 Update Logistics	5	8
7.4 Part Information Gathering	.5	2
7.5 Criticality Determination	.25	1
7.6 Airworthiness Assessment	.25	2
7.7 Feasibility Assessment	.25	4
7.8 Part Classification	.25	.5
7.9 Classification approval/Notification	.25	.5
7.10 Update AM Database	.25	.5

b. Print Times and Failure Rates (`print_dict`)

This section describes in detail the logic behind heuristically deriving the print times modeled per print level and the procedural rationale for selecting print failure rates. Part approval growth rate, like the print failure rates mentioned in the previous section, are highly variable. Extreme temperatures, humidity, and the stability of the printer itself (i.e., does the printer remain stationary and undisturbed during production?) all impact print quality. Factors such as sea state or resonate frequencies from propulsion equipment on a U.S. Navy ship would likely need to be considered and mitigated for consistent AM.

Influencing the decisions for these initial build times and failure rates were captured by speaking with fleet AM printer operators and the author’s testing and use of Level 1 and 3 AM assets with Naval Postgraduate School laboratories (Jones 2022). Table 12 displays the initial values.

Table 12. Initially Modeled Build Times and Build Failure Rates

Print Level	Initial Build Time in Days	Initial Failure Rate
1	1,2,3	5%
2	1,2,3,4	15%
3	1,2,3,4,5	33%

2. Controlled Input Parameters

In total, twenty-nine input parameters produce seventeen primary output statistics. Table 13 summarizes each of the input parameters used in the model. The simulation reads scenario parameters from a "*Levers.xlsx*" file for rapid adjustments and iterations between trials. The algorithms within the model equivocate and imply linear time complexity *O(n)*, confirmed by the proportionality of runtime growth to increases in the number of simulated orders instantiated within each scenario trial. The model can be run with various input parameter values to generate different output statistics. We use these output statistics to compare the performance of the order fulfillment process under different conditions and cover this in more detail in Chapter V.

We designed the simulation model to mimic the real-world order fulfillment process as closely as possible, using data from actual 9B COG orders. We use this order data, merged with the additional heuristic input sources, to sample probabilistic limits for various simulation aspects, such as order size and shipping time. Adapting a descriptive methodology from Biles (2021), the parameters are passed into the model as input from the user and remain constant throughout the simulation. This enables the flexibility to explore various scenarios and examine the impact of changes on specific portions of the maintenance cycle.

Table 13. Table of Simulation Model Input Parameters, Descriptions, and Associated Functions

Parameter Name	Category	Description	Associated Function(s)	Phase Called
Days	Instantiate Orders Per Day	Range of days covered by model	*Create_poission_sequence, Generate_demand*	Phase 1
Limit	Instantiate Orders Per Day	Total number of orders simulated during the test range	*Create_poission_sequence, Generate_demand*	Phase 1
Last_Day_Limit	Instantiate Orders Per Day	Limit on final simulation day, to keep each preceeding simulation day within parameters	*Create_poission_sequence, Generate_demand*	Phase 1
Lambda	Instantiate Orders Per Day	Mean number of orders from sample groups, forms Poisson Distribution	*Create_poission_sequence, Generate_demand*	Phase 1
quantity_range	Assign Quantities Per Day	Total range of order quantities to simulate	*Assign_Quantity, Generate_demand*	Phase 1
majority_range	Assign Quantities Per Day	Range of most probable order quantities to simulate	*Assign_Quantity, Generate_demand*	Phase 1
majority_prob	Assign Quantities Per Day	Probabilistic threshold to favor majority range	*Assign_Quantity, Generate_demand*	Phase 1
weights_dictionary	Simulate Weights	Simulated Weight Parameters and Probabilistic thresholds for each	*Build_weights_list, Generate_demand*	Phase 1
closed	SameDay OpenClose Percentage	Probabilistic threshold to simulates orders fulfilled via local inventory	*Generate_demand*	Phase 1
still_open	SameDay OpenClose Percentage	Probabilistic threshold to pass remaining orders to next phase	*Generate_demand*	Phase 1
Day_Splits	Conditions for Print_Probability	List segmenting simulation day range into groupings by year	*Separate_Print, Isolate_Print*	Phase 2
probs_w_print	Conditions for Print_Probability	Probabilistic thresholds considering orders for AM. Deterministic	*Isolate_Print*	Phase 2
print_prob	Conditions for Print_Probability	Probabilistic thresholds orders are sourced to the respective print node	*print_assign_day, create_print_list*	Phase 2
print_list	Conditions for Print_Probability	List of print node names	*create_print_list, assign_print_days, df_Add_print_days*	Phase 2
print_dict	Conditions for Print_Probability	Print time day ranges and probabilistic threshold of print failure	*print_assign_day, assign_print_days, df_Add_print_days*	Phase 2
non_print_nodes	Probabilities for Each Subset of Nonprint	List of non-print node simulated distribution center names	*assign_node_day, df_Add_node_days*	Phase 3
subset1	Probabilities for Each Subset of Nonprint	Grouping of simulated closest to customer distribution center nodes	*df_Add_node_days*	Phase 3
prob_1	Probabilities for Each Subset of Nonprint	Probabilistic thresholds orders are distributed to nodes in subset1	*assign_node_day*	Phase 3
subset2	Probabilities for Each Subset of Nonprint	Grouping of simulated next closest to customer distribution center nodes	*df_Add_node_days*	Phase 3
prob_2	Probabilities for Each Subset of Nonprint	Probabilistic thresholds orders are distributed to nodes in subset2	*assign_node_day*	Phase 3
subset3	Probabilities for Each Subset of Nonprint	Grouping of simulated furthest from customer distribution center nodes	*df_Add_node_days*	Phase 3
prob_3	Probabilities for Each Subset of Nonprint	Probabilistic thresholds orders are distributed to nodes in subset3	*assign_node_day*	Phase 3
Split_1	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 21 - 90 days, remaining orders sent to Split_2	*Phase_3_splits*	Phase 3
Split_2	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 91 - 365 days, remaining orders sent to Split_3	*Phase_3_splits*	Phase 3
Split_3	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 366 - 1000 days, remaining output as "lost.csv"	*Phase_3_splits*	Phase 3
p_Bin_A	Added Days simulating transportation time	Assign binary probability that order falls into transportaiton mode A	*Add_Bin_Days*	Phase 4
weight_condition	Favors transportation mode based on order weight	Sets probabilistic thresholds based on orders weigh for transportaiton mode A or B	*Add_Bin_Days*	Phase 4
Bin_A	Added Days simulating transportation time	Transportation mode A day range	*Add_Bin_Days*	Phase 4
Bin_B	Added Days simulating transportation time	Transportation mode B day range	*Add_Bin_Days*	Phase 4

B. THE MODEL

This thesis explored eight distinct scenarios in evaluating an operationalized AM versus the current supportability model. The first four scenarios all sample the demand schedules based upon the sample groups in Table 14, first mentioned in the Chapter III heuristic development section. For example, Scenario (1) is the baseline model of the current spare parts supply chain, simulating the current-state supportability model without AM as an order fulfillment source.

Table 14. Initial Sample Groups by Printability Score

Printability Score Range	Printability Percentile	Output Group Name
0 - 14	0 - 25%	no_print.csv
15 - 18	26 - 50%	low_print.csv
19 - 24	51 - 75%	med_print.csv
25 - 37	76 - 100%	high_print.csv

Scenario (2) adds AM as an order fulfillment source and assumes a conservative part approval growth rate. Scenario (2) starts with 450 parts approved for printing and adds an additional 450-part approval every 365 days of simulated run time. By the end of the simulated 1100-day run time, the model assumes roughly 0.5% of all orders are approved for printing. Figure 8 depicts the linear part approval growth rate employed in Scenario (2).

We undertake scenarios (3) and (4) to evaluate and stress print node utilization rate and provide insight into how printing a great deal of orders either positively or negatively impacts lead time. Scenario (3) keeps the same input parameters as the last two scenarios; however, it evaluates a logistics growth curve for part approval growth instead of a linear growth curve. This logistics growth curve begins with the same growth rate as Scenario (2), followed by exponential growth before shifting to slower logarithmic growth, producing an S-shaped growth curve. This equated to roughly 2.5% of all orders sourced to print nodes by the end of the 1100-day run time. Figure 13 shows a depiction of the logistic part approval growth rate employed in Scenarios (3), (4), (6), and (8).

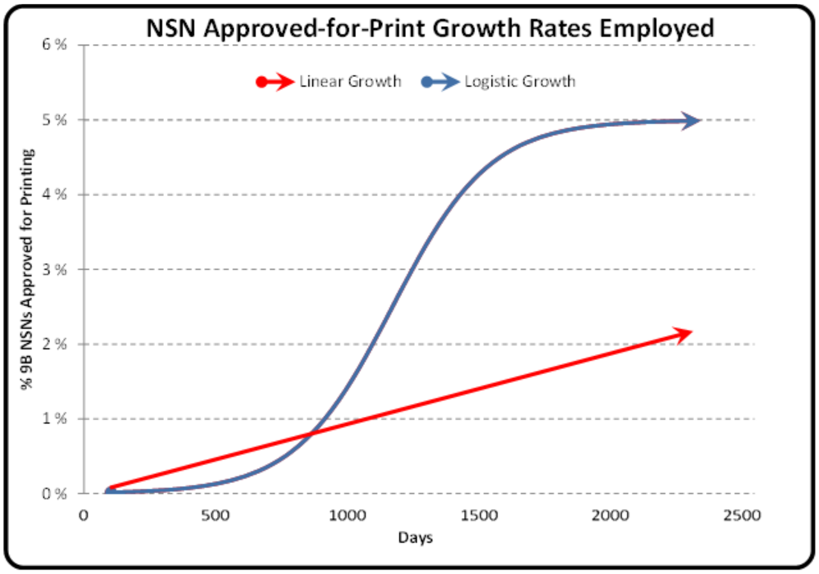

Figure 8. Plot of Linear and Logistic Part Approval Growth Rates Employed in Scenarios with AM

Scenario (4) mirrors the logistic growth from the prior scenario but also assumes and models that print failure rates and post-processing decrease over time. This aligns with a primary assumption that a unit's AM asset operator skills and acumen will improve over time. Also, the print Level 3 improved build time is reduced to a 1–2-day range to simulate the build time improvements enabled by the new liquid metal FDM print technology, which can produce production-ready parts markedly faster than other Level 3 print technology. Table 15 outlines the improvements modeled and examined within Scenario (4).

Table 15. Initial Build Times and Build Failure Rates and Scenario (4) Improved Build Times and Build Failure Rates

Print Level	Initial Build Time in Days	Initial Failure Rates	Improved Build Time Range	Improved Failure Rate Range
1	1,2,3	5%	1,2	2-4%
2	1,2,3,4	15%	1,2,3	10-14%
3	1,2,3,4,5	33%	1,2	20-25%

While the first four Scenarios take a macro-level approach by paralleling the sampled source data, Scenarios (5)–(8) present a micro-level exploration into simulating potential lead time improvements afforded by AM. We achieve these insights by sampling the source data for the moderate to highly printable part orders with the most extended lead times. In addition, these scenarios keep the input parameters from Scenario (3) regarding the new part approval growth, build time, and failure rates.

Scenarios (5) and (6) sample the source data for orders with a printability score greater than 22 that were delivered to the customer and completed between 21 –90 days. Scenario (5) assumes no AM capability within the model, and Scenario (6) includes AM capability as a fulfillment mechanism.

Lastly, Scenarios (7) and (8) parallel (5) and (6) in their sampling methodology and execution; however, the source data sampled is orders with a printability score greater than 22 that were delivered to the customer and completed between 91–1000 days.

1. Overview

The simulation model has four distinct phases, outlined in the proceeding section. Phase 1 generates synthetic orders based on the four different demand schedules sampled by the heuristic in the previous step. In addition, order IDs, day ordered, weight, and order quantity is also assigned. At the end of Phase 1, the model closes a portion of the generated orders and produces its first output file, which simulates the proportion of orders fulfilled by local unit inventory.

Phases 2 and 3 receive and evaluate the remaining records, where simulated orders are "issued" from a global distribution center node, advanced for printing evaluation or contracting as fulfillment sources. Finally, we evaluate a portion of orders for either AM or contracting as fulfillment sources. Within the simulation's AM portion, the model adds days to orders considered for printing, simulating print time, including print failure rates. Conversely, in the contracting model portion, days are added simulating short lead time (30–90 days), long lead time (91–1000 days), and unfulfilled orders taking more than 1000 days to fulfill (9999 days applied and exported to CSV). "Unfulfilled" orders are then output to a CSV file titled "*Lost.*"

Lastly, in Phase 4, transportation time to the customer is simulated, and days are added based on global distribution depots and print nodes shipping to one of the five INDOPACOM geozones, also accounting for order factors such as the weight of order to determine if an order can be say flown to an airwing customer via a carrier onboard delivery aircraft.

Lastly, the model deconflicts data and measures printer utilization rates. All data is remerged, the trial ends, and the model outputs the node performance summary statistics based on days (lead time) and the individual node transaction reports. A flowchart of the simulation's four main phases is found in Figure 9.

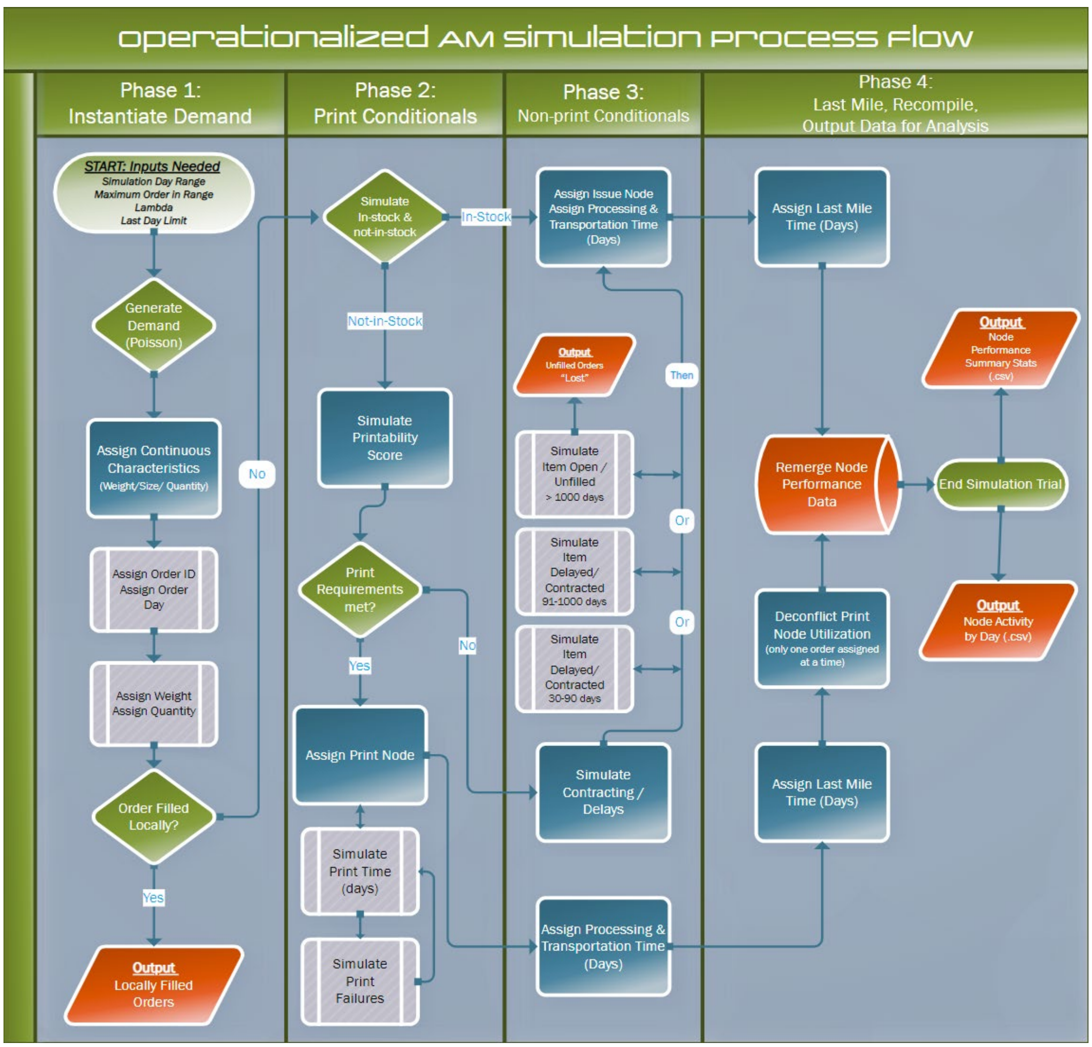

Figure 9. Operationalized AM Simulation Logic Flowchart

We formulate our model as a Monte-Carlo simulation, written in Python. Each of the four main phases are .py scripts containing all the functions and decision logic that execute based on the user-supplied input parameters. We call these scripts from a master Jupyter notebook *Levers_Initiate*. The simulation stores all events in memory during execution and we wrote the simulation model such that extension to broader and more distributed simulation environments is possible in future work efforts. This modality reduces the model's run time and enables minor, compartmentalized simulation logic adjustments within the smaller scripted packages without potentially destabilizing the model. The inputs and outputs are broken down in the proceeding sections, as are the methodologies used for simulating the various stages of the order fulfillment process. Using the printability groups produced by the heuristic evaluation tool we capture the probabilistic thresholds for each decision point, which allows the model to simulate order fulfillment performance within hypothetical but realistic scenarios.

2. Conceptual Model Pseudocode and Assumptions

The full pseudocode detailing the model's functionality, complete with input parameter descriptions, functions, and output processes, is contained within Appendix G. Specific assumptions were made to simplify and realize this conceptual model. Several of these assumptions are adapted from Doudnikoff's research and simulation modeling AM in a military sustainment network (2021), as they remain relevant to this research effort.

a. Orders Are Independent Events

The model assumes independence for each synthetically generated order instance. Therefore, there exist no dependencies within the simulation. However, this may not reflect the seasonality of a unit's repair part requirements based on their operational schedule or the cyclical ordering loops aligning with consistent preventative maintenance events (for example, the 30-day phase maintenance kit for F/A-18F Super Hornet airframes).

b. 9B COG Code Only—Aviation Consumables

The scope of this research covers 9B COG codes only. However, we built the simulation to accept sampled inputs based on other any COG code desired.

c. Stochastic AM Production Time

The time to produce a part via AM is random within the model. This model accounts for a broader measure of print times variability based on the level of AM an order is sourced. We base the time range of between 1–5 days per print on anecdotally captured data points from fleet AM printer operators, as well as the author's testing, understanding, and use of AM assets with Naval Postgraduate School laboratories. We also consider the prescribed manufacturer's machine specifications per AM category to model production time inclusive of post-processing time as well as actual fabrication time. Eventually, when operationalized AM is fully realized, deterministic or near-deterministic print and post-processing times will be available per specific part and will likely be considered in the readiness planning horizon and operational availability.

d. 24 / 7 / 365 Model Performance

This assumption expects 24 / 7 / 365 performance at all print and issue nodes. While a deployed unit places repair part orders with this 24 / 7 / 365 frequency, modeling worker shifts, weekend non-workdays, and holiday node unavailability would add additional complexity outside this research's scope. An additional factor within this assumption is the model's primary time interval, days, as discrete whole numbers. This could lead to stepwise binning of values in certain distributions when plotted. These assumptions, however, presents an opportunity for future refinement and expansion.

e. AM Print Files and Post-Processing Requirements Are Available, Licensed, and Transmittable

Arguably the most Herculean barrier to broad AM deployment is the consistent, secure, and legal transmission of 3D models and GCODE printer instructions for each item sourced for AM. Some post-processing requirements exist for the majority of AM-produced parts. These factors are no longer barriers, and when sourcing an order to a print node, those operators have the digital files and instructions required to fulfill the order. Finally, any underlying considerations for licensing tracing or fees for IP legality purposes occur and are not factors within the simulation.

f. All Raw Materials for Printers Are Readily Available

For this research, all raw materials required for printing are on hand and available. Therefore, adding the raw materials supply chain to this model would add complexity. However, once the availability of relevant demand data and sourcing flow for AM raw materials is prevalent, opportunities emerge for future work by implementing this source modality into the simulation model.

g. AM Orders Are Sourced in the Same Manner as Current Supply System Orders

Presently, requests for items made via AM are non-automated and primarily achieved through manual communications by the customer with supply and maintenance personnel. The model assumes that AM is another viable and ready supply source that underlying DOD supply systems can pass requisitions to automatically. Hypothesizing that this will one day be commonplace, decisions on what to produce via AM will be made upstream within the supply chain, with the warfighter customer simply supplying the demand signal for the requirement.

h. Poisson Demand Schedules Remain Fixed throughout Each Scenario

Demand schedules are discrete events that cannot occur simultaneously and remain fixed from instantiation through simulation end. Policy and the operational tempo remain consistent throughout the time horizon. This is reasonable since the time horizon for the model is limited to approximately 1110 time periods (days). From Law's text *Simulation Modeling and Analysis* (2013), a Poisson process models sequences of discrete events where the average time between events is known, but the specific timing of events is random (i.e., uniformly distributed) conditional on the number of events over a period of time. From our first assumption, its presumed that all orders (events) are independent of each other, and the time between orders is memoryless. With this assumption, the process corresponding to the number of orders matches the primary criteria for a Poisson process. Extending this assumption further, within this simulation, the incidence of one event does not impact the probability that another event occurs. We assume the rate of orders (events) per time period (day and total days) remains constant, which makes the Poisson process homogeneous. From the literature, inclusive of McDermott et al. (2021), Doudinikoff (2021), and Khajavi et al. (2018), properties of intermittent part order demand in many instances are assumed to follow a Poisson process. For these reasons, we employ a fixed Poisson demand schedule to generate synthetic orders within the simulation model, and a deeper exploration into this crucial assumption is found in the Sensitivity Analysis paragraph in Section C of this chapter.

i. No Split Orders across Multiple Distribution Nodes

Often in the current-state supply chain, many order quantities cannot be solely fulfilled by a singular supply warehouse or distribution site. The underlying supply system accounts for these split orders by referring portions of certain orders to alternate locations with available stock to meet customer demand. However, for the intent of this research, a single specific node fills a singular order with no split orders.

j. Consistent Simulated Stock Levels and Issue Performance Times Applied to Distribution Nodes

Doudinikoff (2021) provides the foundation for this assumption, which implies the warehousing of spare parts in this research at locations within DLA global distribution centers. This excludes vendor-direct delivery, non-NSN-supported parts, or parts that historically are not stocked. Warehouse refusals, referring to an occurrence when the supply system indicates a part is available in a specific location, but upon attempted issuance of said part, the physical item is not present, are not modeled within this simulation. We assume that distribution nodes meet IPG 1 and 2 issue response time for every order, which is 24 hours.

k. Print Failure Rates Decrease Year Over Year

Like any manufacturing source, build failures are an omnipresent possibility. In addition, the unique geometries of a part's design may be beyond the capability of the AM asset producing said part. For example, Level 1 FDM printers generally have difficulty printing overhangs within support structures when the overhangs are beyond 60–80 degrees. We detail the logic for modeling print failure rates in Paragraph C of this chapter.

However, a primary assumption is that these print failure rates would decrease over time based on collected data on previous print failures and improved operator proficiency.

l. Deterministic Part Approval Growth Rate

As of June 2022, AM approval for 17 NSN-supported 9B COG parts is in place. In addition, there are an additional 207 that are non-NSN supported. While it is difficult to forecast the length of time and frequency new NSN 9B parts will be approved for AM from NAVAIR Engineering AIR 4.1, estimates for the timeframes for provisional approval of a new part for AM were available and considered. Further detail is provided regarding the part approval growth rate in Section B of this Chapter.

m. No Machine Downtime

While machines being unavailable due to maintenance or causality is realistic within any manufacturing environment, for this research, all three levels of printers are available and operational throughout the simulation. Including AM asset downtime in the simulation would be an opportunity for future exploration.

n. Unit of Issue for All Simulated Orders EA

The simulation does not assign or consider a U/I for the synthetic orders. Therefore, a synthetic order's U/I is each (EA).

o. AM Usage Is Print-to-Order, Not Print-to-Stock

We assume print-to-order is the reasonable AM use case. However, before adopting a print-to-stock modality, printing for shelf stock must be further explored as a feasible and sustainable AM use. A future exploration within the supply chain for repair parts, incorporating print-for-stock as a channel for satisfying AM orders, might be a valuable advancement of this research effort.

p. AM Production Is Constrained to a Single Order per Stochastically Assigned Time

This is a limiting assumption associated with the model implementing "batching," as it could lead to increased build failures. The AM portion of the simulation model is not configured with an inherent waiting pool but rather deconflict and calculates AM machine utilization rate after a simulation print job has occurred. Therefore, the model simulates the fabrication of orders on hand each day, pending machine availability, and does not wait for enough orders to "fill" a batch size. For example, Doudinikoff (2021) states that if AM capacity is dedicated to a specific part, then "the AM machine can only use its capacity to produce that specific part in that specific time." At the same time, we consider order quantity within each stochastically assigned print time range, however we assume that multiple quantity orders could be printed simultaneously in the same print job, a capability of modern AM machines.

C. OUTPUT ANALYSIS

The simulation model creates four explicit output files for analysis. Each scenario runs for forty trails, producing four distinct output files *Same_Day, Lost, Node_Summary,* and *Node_Performance*. The model sequences the forty output files by trial, then combined all to create individual scenario summary files for evaluation and analysis. If required, *Same_Day* and *Lost* are concatenated and available for model verification and analysis. The *Node_Summary* and *Node_Performance* scenario summary files are also concatenated to compare performance across scenarios. As the primary performance measure is lead time, a lower value per measure indicates a more favorable result. Table 16 shows an example of two combined scenario summary statistics, the measures of central tendency, AM machine utilization rate and scenario net effectiveness order fulfillment rate. Chapter V covers a complete analysis of each scenario's outputs.

Table 16. Example Combined Scenario Output Summary Statistics for Baseline Scenarios

	Summary Statistics - Leadtime (Days)					Quartile Ranges (Rounded up to nearest whole number)					Machine Utilization Rate			Net Effectiveness (Orders filled / Total Orders)		
Scenario	Count	Mean	Std Dev	Variance	Skew	Min	25%	50%	75%	Max	Print1	Print2	Print3	Total Filled	Total Orders	Net Eff Rate(%)
Baseline - No Print Capability	401204	32.56	111.37	12403	0.742	3	4	5	7	983	N/A	N/A	N/A	384298	401204	95.8%
Baseline - Print Capability, Linear New Part Approval Growth	401202	29.59	103.8	10774	0.682	3	4	6	7	674	17.6%	9.3%	30.8%	387427	401202	96.6%

D. MODEL VERIFICATION, VALIDATION, AND SENSITIVITY ANALYSIS

After developing this simulation model, we perform measures to verify and validate the model's performance. We undertake these steps to understand how sensitive the model is to input changes and whether the system is operating as expected. The goal of simulation verification, outlined by Günes (2012), is that we must "verify the model is built correctly, complete with correctly implemented good input and structure."

The verification phase begins by examining the distribution of the source data and comparing this data to the chosen Poisson distribution, which generates synthetic demand within the model. The Poisson distribution probability mass function describes the "probability of obtaining k successes during a given time interval." Applied to this research, we can generate a statistically significant demand schedule for employment within the simulation model by sampling the source data from the left chart in Figure 10 to achieve an input parameter *lambda*. An example of the synthetically generated demand data utilizing the input parameter *lambda*, the average lead time by sample group from the source data, leverages the Poisson distribution shown in the right chart of Figure 10.

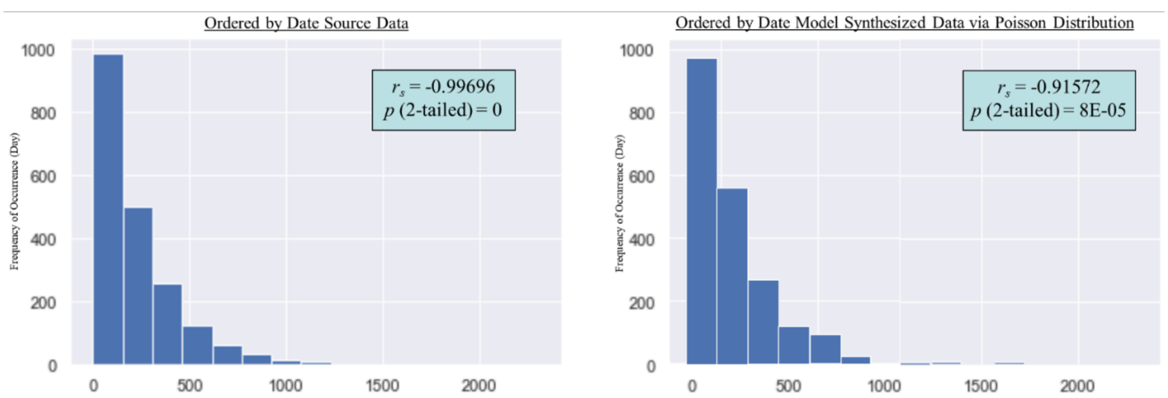

Figure 10. Distribution of Source Data by Ordered Date versus Synthetically generated data

We perform a Spearman's correlation and 2-tailed t-test to verify the Poisson demand generator's fit. These tests are selected to examine the goodness of fit between the source INDOPACOM deployed three-year 9B COG demand data and the synthesized demand data. The p-values from each 2-tailed t-scores are less than 0.0001, indicating a statistical significance between the source and synthetic demand data sets. Each distribution in Figure 10 also illicit a decreasing monotonic pattern as monotonic data tends to decline but not linearly. Figure 11 illustrates the negative monotonic trend seen within the source data distribution from the left chart in Figure 10 with an overlayed trend line.

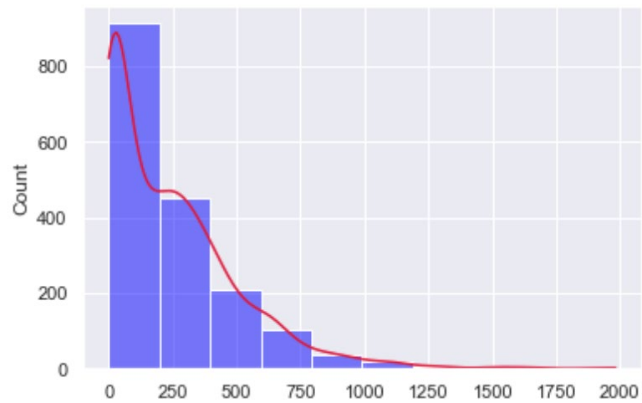

Figure 11. Source Data Negative Monotonic Trend Depicted

Since we observe a decreasing monotonic relationship between the source and synthetic demand data, we evaluate Spearman's correlation value for each data set, as this test requires data to be continuous and follow a monotonic relationship. Using Spearman's rank correlation coefficient r_s, when comparing the $r_s = -0.99$ value for the source data with $r_s = -0.915$ for synthetic data, shown in Figure 11, an approximately 93% fit of the synthetic demand data to the source data presents. By usual standards, the association between the actual and synthetic demand data generated via a Poisson distribution would be considered statistically significant and, therefore, valid for this research.

For final validation measures, we compare the output of lead time data from actual DOD and Naval supply and fulfillment centers with the synthetic lead time performance data per node. This is a critical evaluation to ensure the correct breakdown of parts flows through the simulation network, which leads time outputs to align with actual source data performance, and that lead time performance per node makes sense. Table 17 outlines the summary statistics from actual global supply nodes in yellow and synthetic supply nodes in green. We identify each real site by its three-character routing identifier code (RIC). For example, RIC PKZ refers to Naval Air Station Support Detachment Whidbey Island, Washington. Synthetic sites are simulated as DLA global distribution supply centers and identified by their four-character site abbreviations.

An example is DDBC, which refers to Defense Logistics Agency Distribution Barstow, California. Table 17 shows an assessment comparing the actual versus synthetic order counts and performance parallel to one another and are statistically significant. The last validation measure worth mentioning, also shown in Table 17, is that the model does not source to "*print1/2/3*" in scenarios that are modeling current state supportability paradigms with no AM order fulfillment capability.

Table 17. Source Data Summary Stats Node Lead Time per Order versus Simulation Scenario (1) and (2) Synthetic Node Lead Time per Order

Source Data Highly Printabile Sample Group Actual DoD Issue Point Performance											
Real Loc	PKZ	POZ	Q53	SCH	SCN	SDD	SDF	SDT	SDU	SGW	Total Count
count	44	41	52	33	66	46	47	71	66	51	517
mean	31.09	16.82	30.98	22.87	36.31	39.8	24.61	23.19	33.22	44.82	
std	73.08	65.69	36.72	143	12.26	109.5	32.45	18.13	58.41	64.11	
min	6	7	1	4	1	2	1	1	2	1	
25%	12	12	3	15	11	14	10	13	16	17	
50%	16	15	11	21	18	20	14	17	21	26	
75%	22	17	44	28	45	40	28	23	35	43	
max	384	82	161	50	478	439	178	109	480	409	

Scenario 1 (No Print Capability) Highly Printabile Sample Group Node Performance Output Example											
Sim Loc	DDBC	DDDC	DDDK	DDGM	DDJC	DDNV	DDPH	DDPW	DDSP	DDYJ	Total Count
count	53	49	58	49	47	55	45	48	61	54	519
mean	24.13	8.939	6.483	29.55	6.319	8.655	6.778	8.396	3.967	8.426	
std	126.1	17.26	11.85	106.1	12.26	15.93	13.24	15.48	1.472	15.35	
min	3	2	2	2	2	3	2	3	2	2	
25%	5	3	3	4	4	4	3	4	3	4	
50%	5	4	4	5	4	5	4	5	4	4	
75%	7	5	5	6	5	6	6	7	5	6	
max	923	92	81	561	88	90	83	93	8	80	

Scenario 2 (With Print Capability) Highly Printabile Sample Group Node Performance Output Example												
Sim Loc	DDBC	DDDC	DDDK	DDGM	DDJC	DDNV	DDPH	DDPW	DDSP	DDYJ	print2	print3
count	58	48	44	53	45	54	44	54	51	57	2	11
mean	20.69	7.646	16.7	35.68	4.689	9.296	7.523	6.611	6.882	5.877	5.5	5.818
std	108.1	13.92	64.82	140.5	5.431	13.91	15.01	6.092	13.08	9.337	2.121	2.183
min	3	2	2	2	2	3	2	3	2	2	4	2
25%	4	3	3	3	3	5	3	5	3	4	5	5
50%	6	4	4	4	4	6	4	5	4	4	6	6
75%	7	5	6	5	5	7	6	7	5	6	7	7
max	828	69	429	810	39	70	84	49	71	74	7	9

Continuing to the validation phase, Günes (2012) asserts that the validation phase "must ensure model that operates as an accurate interpretation of the entire system." This phase ensures the model accurately portrays the system to validate our simulation design. A measure to validate the model provides a good approximation of the system can be seen when comparing the simulated net effectiveness data to the source data net effectiveness. Recalling the net effectiveness score for 9B COG orders introduced in Chapter III Part D, the source data presented a 96.41% net effectiveness. Table 18 portrays net effectiveness scores from the synthetically generated orders within each scenario. Scenarios (1) through (4) all fall within plus or minus one percentage point of the source data net effectiveness score. Moreover, since scenarios (5) through (8) are subgroup simulations, which we cover in more detail in the next chapter, the lower effectiveness rates do not need to be considered during the validation phase.

Table 18. Scenarios Synthetic Net Effectiveness Rates

	Summary Statistics	*Net Effectiveness (Orders filled / Total Orders)*		
#	**Scenario**	**Total Filled**	**Total Orders**	**Net Eff Rate(%)**
1	*Baseline - No Print Capability*	384298	401204	95.8%
2	*Baseline - Print Capability, Linear New Part Approval Growth*	387427	401202	96.6%
3	*Print Capability, Logistic New Part Approval Growth*	385750	398931	96.7%
4	*Print Capability, Logistic New Part Approval Growth, Level 2/3 Print time/Failure reductions*	386165	398930	96.8%
5	*21 - 90 Day Sample Group w/ No Print Capability*	29893	32220	92.7%
6	*21 - 90 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	30002	32214	93.1%
7	*91 - 1000 Day Sample Group w/ No Print Capability*	55496	66557	83.3%
8	*91 - 1000 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	56977	66561	85.6%

To conclude our evaluation of the operationalized AM simulation model covered in this chapter, we perform a sensitivity analysis to assess which parameters directly change the simulation results. The standard method leveraged in this research was to vary one simulation model input at a time while holding all other inputs constant. This method provided insight into the model's sensitivity to changes in particular inputs. Employing this analysis tactic illuminated the model's sensitivity to variations in the printability sample groups feeding the model. The printability heuristic produced initial sample groups that considered any order with a printability score greater than or equal to 25 as 'highly printable.' When varying the heuristic to yield sample groups where any order with a printability score of greater than or equal to 17, we consider that mean printability score from the source data as 'highly printable,' the mean lead time for this new sample group increased almost 50% over the initial results. We can infer that other factors aside from chance affect lead time performance when the model is 'overloaded' with larger sample groups of moderately and highly printable orders. Table 19 gives an example of some of the summary statistics output by the simulation.

Table 19. Baseline Scenarios versus Sensitivity Analysis Adjusting Printability Score Ranges within Sample Groups

	Summary Statistics - Leadtime (Days)					Quartile Ranges (Rounded up to nearest whole number)				
Scenario	Count	Mean	Std Dev	Variance	Skew	Min	25%	50%	75%	Max
Baseline - No Print Capability	401204	32.56	111.37	12403	0.742	3	4	5	7	983
Baseline - Print Capability, Linear New Part Approval Growth	401202	29.59	103.8	10774	0.682	3	4	6	7	674
Rebaseline - SA - Print Capability	397654	45.3	119.33	14240	0.711	3	13	17	22	799

The final insight gleaned during the sensitivity analysis of the simulation is found when varying multiple model inputs simultaneously, specifically the `Days`, `Limit`, and `pval(Lambda)` inputs. We learn that due to the build of our Poisson demand generator, these three simulation inputs must all be adjusted in conjunction with one another for the model to generate synthetic demand. This is due to the Poisson demand generation sequence code attempting to find a near exact matching distribution using the number of days input and the total number of desired orders with the given *lambda* value to model the distribution of generated orders. An opportunity for future work is making the Poisson demand generator more elastic and able to accept a range of more varied input values.

We conclude this chapter by outlining the operationalized AM simulation model. The next chapter evaluates the model with results analyzed for several scenarios with different input values.

V. ANALYSIS OF RESULTS

Our simulation results show potential target lead time expectations for 9B COG orders and indicate an approximately 10% lead time reduction across all orders. By analyzing the output values from the initial heuristic sample groups as well as the eight modeled scenarios, we uncover several areas of insight worthy of deeper consideration within future AM supply chains. These include potential lead time improvements when incorporating AM, a holistic profile of the most highly printable orders, an examination into advancing newly approved AM parts into the supply chain, and simulated AM machine utilization rates.

A. LEAD TIME REDUCTIONS WITH AM AS ALTERNATIVE FULFILLMENT SOURCE

Employing AM for order fulfillment, simulation results indicate a lead-time reduction of 10%. This translates to approximately 3 days across all orders when we employ AM as an order fulfillment source in DON supply chains. This finding also assumes the most conservative linear part approval growth rate, where the supply chain fulfills only 0.5% of orders via AM. This translates to 2,750 9B COG orders fulfilled via AM over three years. Using the current number of AM assets distributed within the INDOPACOM AOR, this number of orders would require the annual fulfillments of approximately seventy-seven print orders on Level 3 AM assets, approximately twenty-two orders on Level 2 assets, or some combination of all print levels. Table 20 outlines these eight scenarios and their summary statistics and quartile ranges.

The lead time standard deviation decreased by 8% between scenarios (1) and (2), indicating an increased level of reliability when predicting future order lead times when AM is an order fulfillment source. Figure 12 depicts a box and whisker chart of lead times across the first two scenarios modeled, with the single circular point representing the mean lead time experienced by orders in each subgroup.

Table 20. Scenarios Modeled with Summary Statistics and Quartile Range

	Summary Statistics	*Leadtime (Days)*			*Quartile Ranges (Rounded up to nearest whole number)*				
#	Scenario	Count	Mean	Std. Dev	Min	25%	50%	75%	Max
1	*Baseline - No Print Capability*	401204	32.56	111.37	3	4	5	7	983
2	*Baseline - Print Capability, Linear New Part Approval Growth*	401202	29.59	103.8	3	4	6	7	674
3	*Print Capability, Logistic New Part Approval Growth*	398931	44.97	117.61	7	13	17	22	764
4	*Print Capability, Logistic New Part Approval Growth, Level 2/3 Print time/Failure reductions*	398930	45.85	118.29	7	13	17	21	743
5	*21 - 90 Day Sample Group w/ No Print Capability*	32220	94.7	139.52	3	51	67	84	1002
6	*21 - 90 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	32214	79.36	115.45	3	43	57	71	836
7	*91 - 1000 Day Sample Group w/ No Print Capability*	66557	93.75	137.81	3	51	67	83	1005
8	*91 - 1000 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	66561	79.15	114.9	3	44	57	71	839

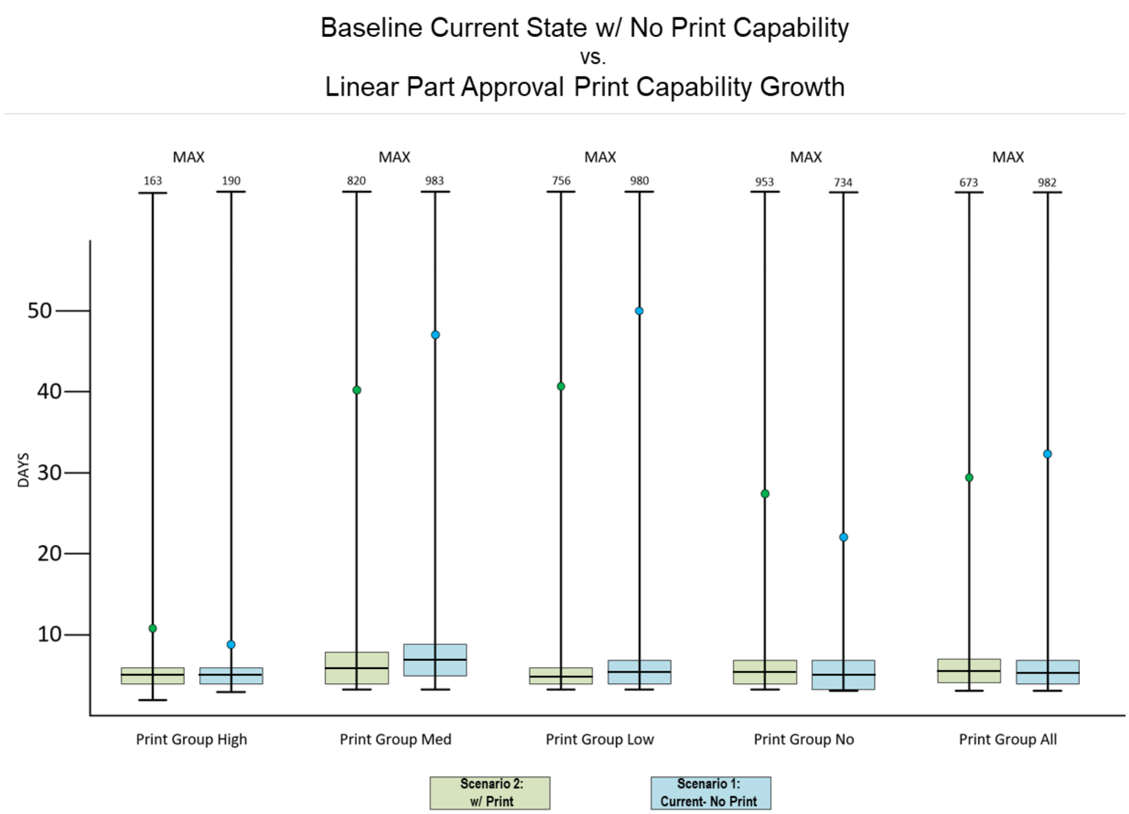

Figure 12. Baseline Scenarios Lead Time Performance by Sample Grouping

At a macro-level view of the scenario's overall output, the benefits of additive manufacturing (AM) are present but uncertain due to high standard deviations. Standard deviation and mean are sensitive to outliers in data distribution. Long lead time orders in the simulation results, derived from the probabilistic flows of the sample source data, have a disproportionate impact on the results, making it difficult to gain vital insights. Furthermore, after 40 simulation trials per scenario, the output results tend to be non-normal.

Table 21. Scenarios (1) through (4) Output Summary Statistics, Inclusive of Variance and Skew

	Summary Statistics	***Leadtime (Days)***				
#	**Scenario**	**Count**	**Mean**	**Std. Dev**	**Variance**	**Skew**
1	*Baseline - No Print Capability*	401204	32.56	111.37	12403	0.742
2	*Baseline - Print Capability, Linear New Part Approval Growth*	401202	29.59	103.8	10774	0.682
3	*Print Capability, Logistic New Part Approval Growth*	398931	44.97	117.61	13832	0.713
4	*Print Capability, Logistic New Part Approval Growth, Level 2/3 Print time/Failure reductions*	398930	45.85	118.29	13993	0.732

Given the inherently non-normal and skewed Poisson distribution, the aggregated results of forty trials per scenario reject the normality assumption. To align with the Central Limit Theorem, data transformations and tests are performed to identify the type and extent of non-normality present. Rerunning the models for tens of thousands or millions of additional trials would be too computationally intensive for this research. Each scenario, consisting of four sample groups, took approximately 8–12 hours for forty trial runs, totaling around 100 hours for all eight scenarios, including test runs. This was executed on an Intel® Xeon® E-2276M 6 Core CPU with 128 GB of RAM and 16GB of VRAM.

Since thousands of additional trials would be needed to solve the non-normality presented, we focused our analysis on lead time performance, specifically in Scenarios (5) and (6). These scenarios were selected to explore how using AM as a fulfillment mechanism could improve lead times for longer lead time orders requiring a contracting action. We resampled only longer lead time orders fulfilled by contracting actions in the

21–90 day and 91–1000-day range in Scenarios (5) through (8). Each Scenario pair modeled identical input parameters, with AM fulfillment included in Scenarios (6) and (8) but not in Scenarios (5) and (7). Figure 13 shows the results of these scenarios using a box and whisker chart.

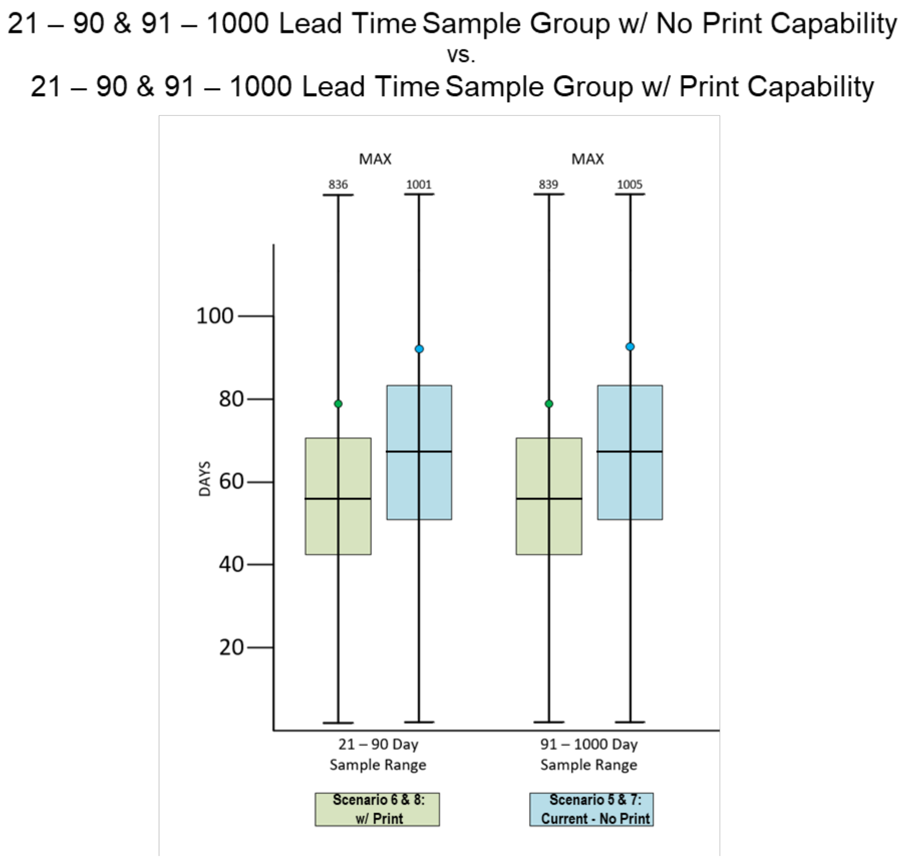

Figure 13. Long Lead Time Contracted Orders Sample Groups Simulated Lead Time Performance Inclusive and Exclusive of AM

In Figure 13, using AM as a fulfillment source in place of contracting for long lead time 9B COG orders, reduced lead time by about 14 days for orders that typically need more than 21 days to complete. It also reduces the standard deviation by approximately 24 days, improving future order forecasting and delivery time estimates. The AM model also produces about 5.9% fewer extreme long lead time orders compared to the non-AM model for orders taking > 1000 days. Table 22 summarizes the effect of AM on lead time.

Table 22. Scenarios (5) through (8) Output Summary Statistics

	Summary Statistics	Leadtime (Days)		
#	Scenario	Count	Mean	Std. Dev
5	*21 - 90 Day Sample Group w/ No Print Capability*	32220	94.7	139.52
6	*21 - 90 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	32214	79.36	115.45
7	*91 - 1000 Day Sample Group w/ No Print Capability*	66557	93.75	137.81
8	*91 - 1000 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	66561	79.15	114.9

However, the results are disproportionately skewed due to the small percentage of orders with extremely long lead times or that are left unfulfilled. The large standard deviations indicate high variance in the data about the sample mean. We see this in Table 25, with tightly clustered inner-quartile ranges, with extremely high maximum values for outer quartile ranges. To address this issue, we perform further explorations and transformations to counter the effects of the long lead time orders skewing the simulation results while preserving the real-world scenarios.

We use the Shapiro-Wilk test to compare the estimated model to actual observations and account for outliers in the data. We perform two separate tests, one with and one without long lead time order outliers, to provide a more accurate representation of skew and high standard deviations. Table 23 summarizes the statistics with greater robustness towards the outliers, quantifying the impact of long lead time orders on these measures.

Table 23. Shapiro-Wilk Test Summary Statistics, Scenario (5) Results

Shapiro-Wilk test Summary Statistics		
	With Long Lead Time	Without Long Lead Time
Mean	12.1108	4.5847
Median	5	4
Standard Deviation	57.6358	1.6543

When long lead time orders are removed, the standard deviation results in a more consistent distribution that is closer to normal. Figure 14 shows a quantile-quantile (QQ) plot and histogram distributions from the Scenario (5) Shapiro-Wilk tests, which illustrates the impact of long lead time orders on the results.

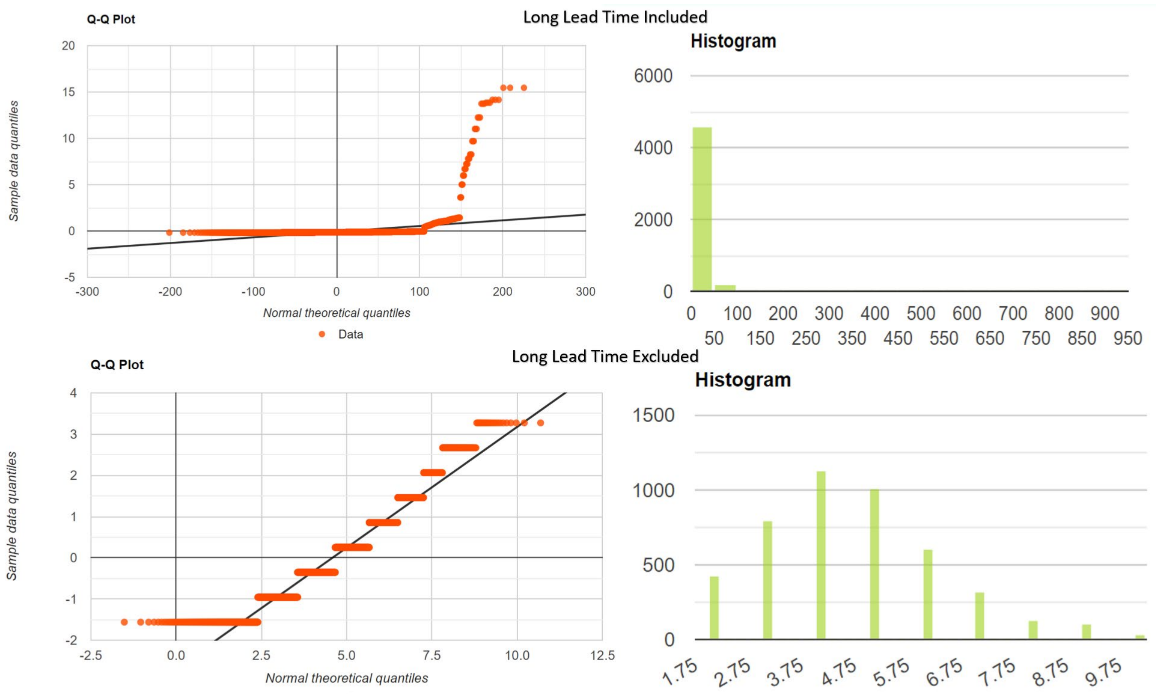

Figure 14. Scenario (5) Shapiro-Wilk tests QQ Plot and Histogram

The staircase pattern in the bottom left QQ plot of Figure 14 is a predictable side-effect of output data discreteness. Aside from the right skewness of the outlier-free data, the results are more normally distributed compared to the plots, including the longer lead time outlier data. Departures from the symmetry of a results distribution in QQ plots are seen by departures from the parity of the binned quantiles.

To examine the distribution of lead times cumulatively, we explore the Pareto plots in Figure 20 using the results from Scenarios (5) and (6). Equipped with a clear understanding of the moderate asymmetric skew of the output results as a measure of lead time gains from AM, these plots serve to help us examine the distribution of lead times.

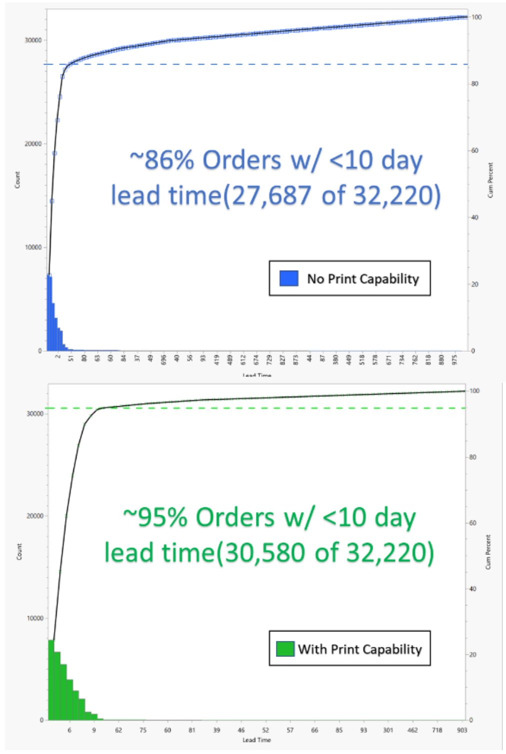

Figure 15. Pareto Plots of Scenario (5) and (6) Count vs. Lead Time Output Results

Of note, it is now apparent the preponderance of orders are fulfilled in ten days or fewer across these two scenarios. This is reasonable given the initially presented inner quartile ranges. These results offer more definitive impacts that AM could have on 9B COG lead time, especially for orders historically filled via contracting and longer lead times. Figure 15 illustrates the potential lead time and order fulfillment improvements afforded by AM, with an additional nine percentage points of orders filled in ten days or less in the scenario with AM fulfillment capability. These results present when modeled scenarios still include the highly printable, longer lead time contracted orders.

B. HIGHLY PRINTABLE ORDER PROFILE

This research allowed us to create a profile that shows the most common and printable continuous order characteristics from the source data. We used printability heuristic output scores for the 9B orders to create this profile, outlined in Table 24. By using this profile, we can advance newly approved 9B parts to the JDTI for AM fulfillment.

Furthermore, this profile can help filter millions of NSNs and direct the most printable ones to SYSCOM AM groups for evaluation, design, and prototyping. Since customers usually request approval for AM parts from their respective SYSCOM, this profile can serve as a useful framework for future design, prototyping, and evaluation.

Table 24. Highly Printable Continuous Characteristics Order Profile

	Order Characteristic	Values / Codes	Key Insights
1	Federal Supply Class	1560, 1680, 5305, 5310, 5340	Top 5 occuring FSC's: Screws, Airframe Structural Components, Hardware (Access Covers; Bumpers; Casters; Cabinet and Door Hardware; Hinges; Latches), Nuts and Washers, Miscellaneous Aircraft Accessories (Control Assemblies, Actuators,; Ventilators, Relief Tubes; Map Holders, Safety Belts, Harnesses, Electric Windshield Wipers)
2	Cube	0.0169	Average Cube was 0.0169 cubic meters, or 1031 cubic inches. Translating to approximately a 10" x 10" x 10" volume measure
3	Weight	0.467	Average Weight was 0.467 Kg, translating to just over 1 lbs, approximately
4	Unit of Issue	EA	All the most highly printable part orders had a unit of issue of EA
5	Order Quantity	0, 1, 2, 3	Average order quantity was 2.57, so approximately 3 items per order
6	Project Code	AK1, BK0, 706, ZC8, ZK3	Top 5 occuring Project Codes: Partial Mission Capable Support Equipment, Aviation unscheduled repair work stoppage, Not Mission Capabile Supply West Coast, Awaiting Parts for Repair, Engine or major component, Aircraft Flight/Survival Equipment
7	Source of Supply	SMS, NRP	All the most highly printable part orders had contracting as their source of supply. 75% filled by SMS - DLA Aviation, and 25% filled by NRP - NAVSUP WSS
6	Average Lead Time	219	Average order fulfillment lead time for the most highly printable 9B orders, ~219 days
7	NSN	016477464 124075134 014932036	Nomenclature for top three most reordered highly printable parts: 1) FAIRING,WING,AIRCRAFT, 2) UTI RESILIENT MOUNT, 3) SCREW,CLOSE TOLERANCE

C. LOGISTIC NEW PART APPROVAL GROWTH LEAD TIME IMPROVEMENTS

We modeled the growth of logistic part approval to evaluate if there was an inflection point where using AM as a fulfillment source would negatively affect order lead time for a 9B COG order. Our simulation model showed that 2.5% to 2.7% of orders would be fulfilled by AM, resulting in 13,750 to 15,000 orders being fulfilled over a three-year period. Using initial print failure rates of 5% for level 1 prints up to 33% for level 3 prints, we found a compounding effect on lead time due to reprinting failures. We can improve this simulation model by using less subjective input data for AM capabilities as it becomes available. Table 25 covers the lead time increases output by the model during Scenarios (3) and (4).

Table 25. Scenarios (1) through (4) Output Summary Statistics

	Summary Statistics	*Leadtime (Days)*				
#	Scenario	Count	Mean	Std. Dev	Variance	Skew
1	*Baseline - No Print Capability*	401204	32.56	111.37	12403	0.742
2	*Baseline - Print Capability, Linear New Part Approval Growth*	401202	29.59	103.8	10774	0.682
3	*Print Capability, Logistic New Part Approval Growth*	398931	44.97	117.61	13832	0.713
4	*Print Capability, Logistic New Part Approval Growth, Level 2/3 Print time/Failure reductions*	398930	45.85	118.29	13993	0.732

D. INSIGHTS INTO POSSIBLE AM MACHINE UTILIZATION RATES AT SCALE

We used logistic growth new part approval scenarios to stress-test the AM components of the model. Even with 15,000 simulated orders, print nodes only reached a maximum of 75% utilization. This indicates that the 81 naval commercial-quality AM assets we have available for research and development are capable of handling the workload, assuming trained operators and print file availability. Utilization rates by capability level for each scenario are shown in Table 26.

Table 26. AM Machine Utilization Rates by Capability Level Across all Tested Scenarios.

	Summary Statistics	Machine Utilization Rate		
#	Scenario	Print1	Print2	Print3
1	*Baseline - No Print Capability*	N/A	N/A	N/A
2	*Baseline - Print Capability, Linear New Part Approval Growth*	17.6%	9.3%	30.8%
3	*Print Capability, Logistic New Part Approval Growth*	37.6%	23.2%	75.4%
4	*Print Capability, Logistic New Part Approval Growth, Level 2/3 Print time/Failure reductions*	35.4%	21.5%	72.1%
5	*21 - 90 Day Sample Group w/ No Print Capability*	N/A	N/A	N/A
6	*21 - 90 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	N/A	11.15%	30.70%
7	*91 - 1000 Day Sample Group w/ No Print Capability*	N/A	N/A	N/A
8	*91 - 1000 Day Sample Group, Print Capability, Logistic New Part Approval Growth*	N/A	17.01%	32.70%

When simulating high volumes of orders sourced to print nodes, the utilization rate does not reach an upper limit nearing 100%, likely due to several limiting assumptions. This simulation assumes 24 / 7 / 365 node availability to respond to and fulfill incoming orders. AM machine downtime is not considered within the simulation. Both of these factors offer opportunities for future work initiatives, where we consider a realistic worker shift schedule at each node and include machine downtime considerations within the model.

In Figure 16, utilization rates for Print Node 3 during Scenarios (2) and (3) are shown. The simulation spikes utilization above 100% for 53 days in the 1100-day range, but the maximum utilization rate achieved during the run is 75.4% due to lower order rates early in the Scenario. A more refined utilization statistic can be achieved using less subjective part approval growth rate input data once mature and available, coupled with more accurate modeling of real-world machine downtime and worker shift scheduling.

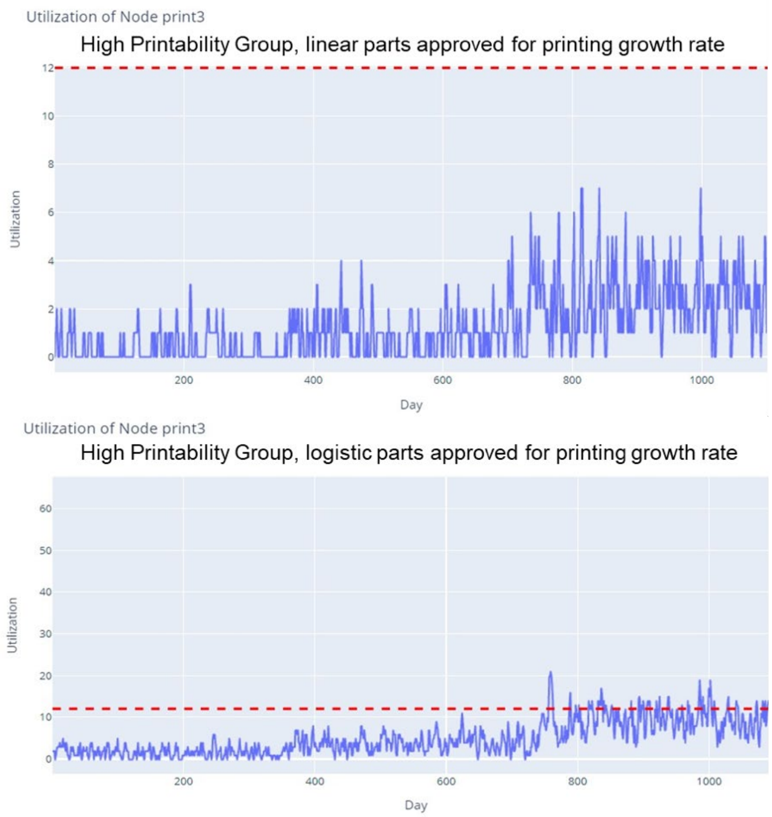

Figure 16. Print Node 3 Utilization Rates during Scenario (2)-top, and Scenario (3)–bottom.

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VI. CONCLUSION

This thesis proposes a method for evaluating the printability of a 9B COG order from its continuous characteristics, along with a simulation model and concurrent evaluation methodology that provide insights into the lead time improvements of an AM fulfillment source. Our approach offers a glimpse into the future of warfighter support through AM. This research will be most effective when paired with alternative evaluation tools currently in development, which consider more engineering and material factors when evaluating a part or order for its potential printability. This methodology can provide more supply-centric methods for planning and employing AM as a fulfillment avenue, making it a valuable resource for ongoing AM implementation.

A. RECOMMENDATIONS

The primary recommendation offered aligns directly with current DOD AM strategic objectives. The sooner we can operationalize AM to produce safe parts while running in parallel with traditional procurement and order fulfillment methodologies, lead time improvements can present enterprise-wide, even when only a tiny segment of orders are fulfilled via AM. This is not a new insight. However, the results illuminate the quantitative levels of lead time benefit potentially gained with an operationalized AM fulfillment source for 9B COG parts and orders.

Next, any efforts to design systems and processes to capture data regarding the deterministic print times per NSN on specific AM machines are paramount to future planning and simulation efforts. Eventually, programming the exact print time per order into a simulation would provide a refined output capable of producing more actionable insights. The same recommendation extends to efforts to capture print failure rates per AM machine. This data currently is only anecdotal, and no formal database captures the print failures rate. Moreover, while the JDTI database tracks new part approvals, in its current state, it captures raw information still maturing. This database is ripe for further analysis of the newly developing approvals rates and trends, as this is a primary input to future demand planning with AM as a fulfillment source.

As AM is a rapidly developing technology, there will likely continue to be procurements of new advanced AM machines for research and development purposes. This thesis attempted to portray the capabilities of the current in place eighty-one commercial quality Naval AM assets for one class of repair parts. While substantial mechanisms, systems, and procedures need to be in place to automatically source customer orders to the operators of these AM machines, there likely exists an intermediate solution where these 81 machines, presently utilized for research and development purposes, can fulfill orders. A database or spreadsheet of back-ordered but printable parts that sites with commercial-qualitative AM assets can work to fulfill. These sites could attempt prints to provide the machine operators valuable experience, then ship the newly printed parts to the COG-specific agency of record for a thorough engineering evaluation of the item.

Finally, further development of this simulation model by validating its comprehensiveness when implemented with AM printability evaluation tools that consider part material and design characteristics is a logical progression of this research. As laid out in our research scope and objectives, a part's design characteristics, as well as an order's continuous characteristic, should both be considered when evaluating just because we can print a part or order does not mean we should print the requirement.

B. LIMITATIONS

There were several limitations within this research:

1. Stochastic Factors Modeled Deterministically

We assume that AM, which can be a deterministic production process, is stochastic in nature for this research. We attempt to account for the expansive nuances of AM, such as machine complexities, performance, post-processing time, built rates, batching capability, and machine build chamber size. These are all measurable and inherently deterministic. However, data is either presently immature and unavailable or points to what would be a profound effort to capture all the deterministic parameters of hundreds of models of AM machines.

2. Point-in-time Source Data

All databases merged into the eventual sample group evaluated by the printability heuristic were sourced by requesting or downloading .CSV files at a specific time. NSN information updates monthly, COG codes and part item managers can change, and customer order transaction data continuously updates as each requirement moves towards delivery. The model could not consider these fluid changes to the source data, and to achieve the highest degree of fidelity, these live databases would need to be integrated into a tool of some kind so that the simulation model can be executed and evaluated.

3. Sensitive Inflexible Demand Generation

A typical supply chain must respond to an ever-changing set of intermittent and seasonal demand parameters. Noted in the sensitivity analysis section of Chapter IV, the demand generation modality employed by the simulation model causes several input parameters, specifically `Days`, `Limit`, and `pval(Lambda)` inputs, to be inextricably linked. As a result, these three parameters must be adjusted in tandem to generate synthetic demand data so the model can produce an output. An elastic, more flexible Poisson demand generator able to accept a range of more varied inputs, which can also model different demand types like intermittent or seasonal demand, would have enabled the evaluation of much more abstract and hypothetical scenarios.

4. Subjectively Derived Model Input Parameters

This research assumed a more mature AM implementation and posture throughout the supply chain. However, the DOD is primarily in a policy development and experimentation phase with AM employment. Therefore, only anecdotal data was available for parameters like part failure rates, new part approval rates, printability evaluation, and build quality of printed parts. No current research evaluated order characteristics as a measure of potential "printability." This research assumed that AM-produced parts were of equal quality to a commercially produced replacement. However, many current AM technologies, dependent on the machine or part material, typically yield a part of lesser quality when compared to the commercially produced alternatives. This would be a key consideration in the real-world operational decision as to which parts and orders can and should be produced via AM, but it is not a feature considered by this research or the simulation model.

The scope of this research also assumed four parameters to deploy and integrate AM into the DOD supply chain effectively:

1. The right machines, materials, and support equipment must be in place, with users trained to operate these AM assets.
2. An IP licensing capture and tracking methodology and process in place, where IP originators of part designs are legally credited and compensated when a DOD user prints a licensed or trademarked part.
3. An integrated approval processes for new printable parts, uncompromising in the engineering, quality testing, and safety standards when approving a part for AM.
4. A cohesive ordering process that interfaces with existing DOD supply systems, enabling a unified effort in supporting the warfighter with conventional process and AM as fulfillment sources.

We base this assessment the narrowly focused scope taken to meet the goal of this research. There are additional parameters, either unknown or not considered by this research, which would be integral factors to successful AM deployment and integration.

C. FUTURE WORK

This research offers numerous opportunities for future work and exploration. For example, several points of issue that served as limitations within the simulation model could be areas to refine the model's input parameters. Some of these included modeling machine downtime and AM machine available due to work shifts and/or off-days into the simulation. Also, including several cost parameters such as engineering design time, raw materials, transportation, and AM operating expenses into the printability heuristic and simulation model would be logical extensions. As aforementioned, building more flexibility into the Poisson demand generator within this simulation, which can also model different demand types, such as intermittent or seasonal demand, would be a valuable addition to this effort. Refining several heuristic evaluation parameters to include more engineering-specific part design information would add a greater level of fidelity to this model.

Given that executing 40 trials of eight scenarios required approximately 100 hours of computation time with a workstation-level computer, rerunning the modeled scenarios tens of thousands or millions of times would likely provide insight and/or correct the non-normality seen in the results. Research leveraging some of NPS's high-performance computing technology would be a natural extension of this thesis and an opportunity for future work.

The initial proposal for this research mentioned testing and modeling dynamic 'Depot' ships as the print nodes (Hauser 2021). This could be an optimization-based extension of this research by modeling a system with mobile and static supply nodes, reducing longer last-mile transportation times. Also, a tool to evaluate where the print nodes should be geographically located to minimize lead time would be an exciting extension of this research.

The most promising extension of this thesis is in collaborating and providing this research to the Navy Price Fighter group and NAVAIR AM division for consideration and utilization into existing ongoing AM research into evaluating part and order printability. The hope is that this research informs current and future AM stakeholders to a small degree on how to best deploy, integrate, and exploit AM technology to best support the warfighter and serve the Nation's strategic objectives.

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APPENDIX A. CATEGORIES OF AM OVERVIEW

The appendix is comprised of direct excerpts from the NAVAIR Engineering Air 4.1 Standard Work Package (SWP4100-0011) Designing for Additive Manufacturing (Schmelzle 2018b).

7.5.1. Vat Photopolymerization: The Vat polymerization process manufactures a part from a model in a container (vat) of liquid photopolymer resin. This resin is cured on a platform layer by layer using an ultraviolet light. Typically, the platform moves the object being manufactured downward after each layer is cured. A diagram of this process is shown in figure 8. Since the liquid material does not provide any structural support, additional support structures are often required. The Vat polymerization process uses Plastics and Polymers (i.e.: UV-curable Photopolymer resin, Visijet range). A typical SLA part is shown in figure 89.

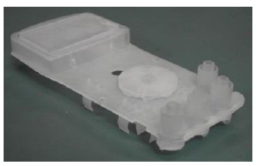

Figure 9: SLA Part

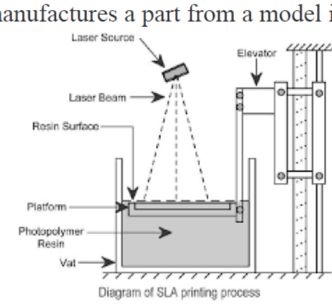

Figure 8: SLA Process

Stereolithography (SLA): SLA is the most common Vat polymerization process. It has a high level of accuracy and a good finish. The typical layer thickness for the process is 0.025 – 0.5mm.

7.5.2. Material Jetting: Material jetting creates objects similar an ink jet printer. As shown in figure 10, Material is deposited from a nozzle which moves horizontally across the build platform where it is solidified using UV light. Typically, the platform will then move downward so another layer can be deposited. The number of materials available is limited due to the material's viscous requirements in the process. Polymers and waxes are commonly used. (Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP). Figure 11 shows and example part made through Material Jetting.

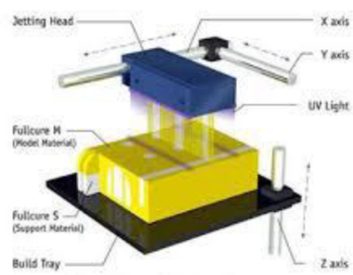

Figure 10: Diagram of Material Jetting process

Figure 11: AM Part through Material Jetting

7.5.3. Binder Jetting: The binder jetting process uses a powder material and an adhesive (binder). A print head deposits alternating layers of the powder and adhesive onto a platform. After each layer, the platform is moved downward so a new layer can be deposited. Typically, a post processing heat treat step is required after the parts are removed from the platform. The binder jetting process can use many different materials and can allow for color prints (Metals, Polymers such as ABS, PA, PC, or ceramics such as glass).

7.5.4. Material Extrusion: The material extrusion process uses material drawn through a nozzle that is heated and then deposited layer by layer onto a platform. After each layer, the platform is moved downward so a new layer can be deposited. It is a commonly used technique used on many inexpensive, domestic and hobby 3D printers. A diagram of this process is shown in figure 12. The Material Extrusion process uses polymers and plastics (Polymers: ABS, Nylon, PC, PC, AB). A typical part is shown in figure 13.

Figure 13: AM Part through Material Extrusion

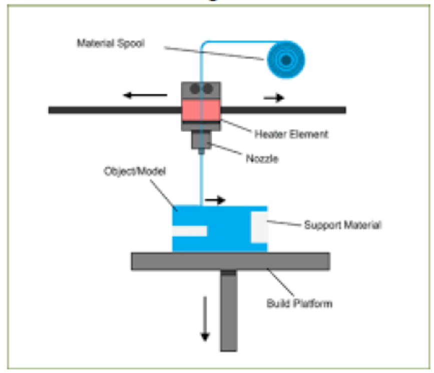

Figure 12: Diagram of Material Extrusion process

Fused deposition modeling (FDM): FDM is a common material extrusion process trademarked by the company Stratasys.

7.5.5. Power Bed Fusion (PBF): Powder Bed Fusion uses either a laser or electron beam to fuse powdered material. During the PBF process, material is spread over a platform using a roller or a blade from a reservoir of powder. The powder is then melted or sintered using an energy source (laser or electron beam). After each layer, the platform is moved downward so a new layer can be deposited. This process is shown in figure 14.

Selective laser sintering (SLS): The SLS process is a Polymer PBF process. It benefits from requiring no additional support structure since the powdered material can provides support throughout the build process. The platform is temperature controlled at a temperature a few degrees below the material melting point. The powdered material is sintered together using a laser.

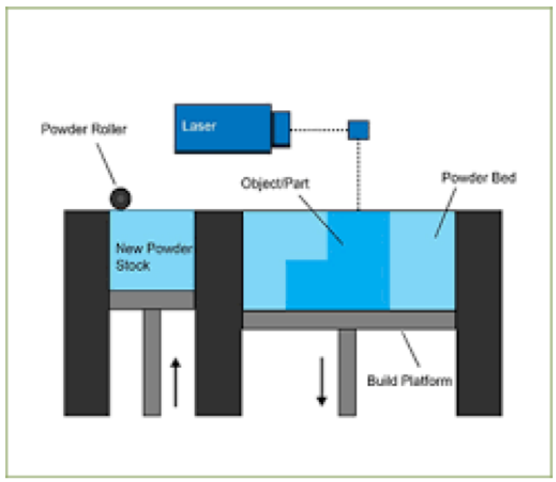

Figure 14: Diagram of PBF Process

Selective Laser Melting (SLM): SLM is similar to SLS except that the powder is completely melted as opposed to being sintered. SLM is usually used specifically for metallic AM.

Direct Metal Laser Sintering (DMLS): DMLS is a powder bed fusion process used to make metal parts directly from metal powders; term denotes metal-based laser sintering systems from EOS GmbH - Electro Optical Systems. Synonym - direct metal laser melting. Although the term implies the metal powder is sintered, is most cases, it is actually melted. A part made through DMLS is shown in figure 15.

Figure 145: AM Part through DMLS

Electron Beam Melting (EBM): EBM is a powder bed fusion process used to make metal parts directly from metal powders. It is similar to SLM except that an electron beam is used to melt the metal powder as opposed to a laser. Consequently, the manufacturing process must take place in a vacuum.

7.5.6**Sheet Lamination:** The Sheet lamination process manufactures parts by binding sheets of material together. A sheet of material is bonded on a platform (cutting bed) and is then cut to shape by a laser or knife. The platform is then lowered; then another sheet of material is bonded on top to form the next layer. The sheet is cut and process repeats itself until the manufacture of the part is complete. A diagram of the process is shown in figure 17 and a typical part is shown in figure 16.

Figure 16: AM part through Sheet Lamination

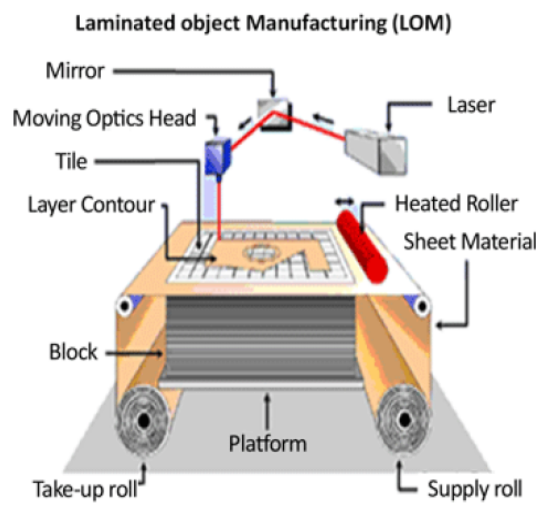

Figure 17: Diagram of the sheet Lamination Process

Ultrasonic additive manufacturing (UAM): The UAM process uses sheets of metal, which are bound together using ultrasonic welding.

Laminated object manufacturing (LOM): The LOM is similar to UAM except that paper is used instead of metal and an adhesive is used instead of welding.

7.5.7 Directed Energy Deposition (DED): DED is an AM process in which focused thermal energy is used to fuse materials by melting material as it is being deposited. The most common DED process, shown in figure 18, blows powdered material through a nozzle, mounted on a multi axis arm, onto a platform or existing part. The material is simultaneously melted using lasers. The nozzle/laser combination acts as a print head as it lays down material layer by layer. The process is similar in principle to material extrusion, but lends itself better to metal materials. A typical DED part is shown in figure 19. Another DED process uses metal wire as its feedstock and lays down material similar to a robotic welder. Typical applications of DED include repairing and maintaining structural parts. Typical materials include Metals such as Cobalt Chrome, Titanium and steel.

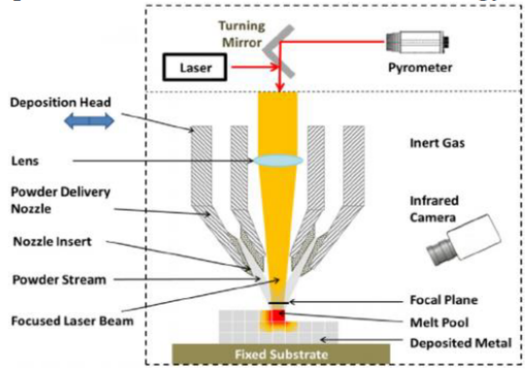

Figure 18: Diagram of the DED Process


Figure 19: AM DED part

Table 8: Advantages/ Disadvantages of the different AM Technologies

AM Technology	Advantages	Disadvantages
VAT Photopolymerization	• High level of accuracy and good finish • Relatively quick process • Typically large build areas: Objet 1000: 1000 x 800 x 500 and max model weight of 200 kg	• Relatively expensive • Lengthy post processing time and removal from resin • Limited material use of photo-resins • May requires support structures and post curing for parts to be strong enough for structural use
Material Jetting	• High accuracy and low waste • Can use multiple materials/ colors	• Support material is often required • Limited materials: only polymers and waxes
Binder Jetting	• Can use different colors (Polymer) • Large range of materials: metal, polymers, ceramics • Relatively fast • Multiple materials can permit a large variety of binder-powder combinations having different properties	• Post processing requirements add significant time
Material Extrusion	• Inexpensive • Plastic can be used that have reasonable structural properties.	• Relatively low speed and accuracy
Powder Bed Fusion	• Relatively inexpensive (polymer) • Powder can act as a support structure during the AM process • Large range of material options	• Relatively slow speed • Relatively expensive (metal) • May require support structure
Sheet Lamination	• Relatively fast • Relatively low cost, • Ease of material handling	• May require post processing
Direct Energy Deposition	• Can be used to repair high quality, functional parts • Can use multiple materials	• Relatively poor surface finish

General Advantages and Disadvantages of Commonly Used AM Polymers

AM Polymer**	Description	Typical Advantages	Typical Disadvantages
Acrylonitrile Butadiene Styrene (ABS)	Commonly used opaque thermoplastic. Traditionally used for injection molding. Sample applications: pipes, medical devices, prototypes (fit check), tooling, support blocks, covers, and housings.	- Insoluble in water - Good impact resistance - Good toughness - Resistant to chemicals - Soluble in acetone for joining parts or achieving smooth finish - Good dimensional stability - Excellent for machining - Easy to paint and glue - Low to mid-cost material	- Properties can vary depending on the chemical composition of input material. Some AM machines produce ABS-like material. - Requires controlled environment (temperature and humidity) during printing. - Input materials must be stored in temperature and humidity controlled environment without exposure to sunlight. - Parts and input materials may deteriorate, discolor, or warp over time if exposed to high temperatures or sunlight. - AM facility should be open and/or well-ventilated.
High Impact Polystyrene (HIPS)	Engineering thermoplastic similar in characteristics to ABS. Often used for low strength structural applications. Sample applications: prototypes, displays, scale models, food packaging, cases, computer housings	- Good dimensional stability - Good impact resistance - Good heat resistance - Excellent machinability - Easily sanded, primed, painted and glued - Low shrinkage value - Non-hygroscopic - Fully recyclable (FDA compliant) - Low cost material	- Flammable (flame retardant grades are available) - Poor solvent resistance - Subject to stress and environmental cracking - Non-toxic, but releases fumes that can irritate the lungs and eyes. The AM facility should be open and/or well-ventilated.
Polyamide (Nylon)	Synthetic thermoplastic commonly used for injection molded parts for vehicles and mechanical equipment. Sample applications: gears, bushings, plastic bearings, build jigs, fixtures, guards.	- Strong, flexible, and durable - Low coefficient of friction - High melting temperature - Good abrasion resistance - Good fatigue resistance - Can be easily dried - Wide range of properties due to its many variants in production. For example: • Nylon 6 and Nylon 66 have high strength and hardness properties. • Nylon 12 is more thermally and chemically stable than Nylon 6 and Nylon 66. • Nylon 12 offers improved impact strength over lower numbered Nylons.	- Prone to shrinkage/warping - Hygroscopic requiring proper storage in an air tight bag with desiccant. - Sensitive to sunlight (UV exposure), requiring cabinet or container storage to limit exposure. - Flammability Considerations
Polycarbonate (PC)	Widely used (typically transparent) industrial thermoplastic. Ideal for prototyping, tooling, fixtures, and patterns for metal bending and composite work. Sample applications:	- High tensile and flexural strength - Good impact resistance, heat resistance, and toughness - Durable and stable - Good electrical insulator - May be easily combined with	- Hygroscopic, resulting in degraded physical properties - Susceptible to shrinkage/warping - Undergoes hydrolysis at high temperatures - Low scratch resistance - AM facility should be open and/or well

AM Polymer**	Description	Typical Advantages	Typical Disadvantages
	protective eyewear/gear, medical devices, automotive components, aerospace components, lighting fixtures.	flame-retardant materials - Can be worked, bent and formed at room temperature - Can be solvent welded with ketones.	ventilated
Polyetherimide (PEI)	An amorphous thermoplastic, well suited for aviation parts. Applications include: prototyping, tooling, electrical housings, medical, automotive, and aerospace (such as ducts).	- High strength to weight ratio - High thermal stability - Excellent electrical properties - Good flame, smoke, and toxicity properties. - Excellent machinability - Good UV and chemical resistance	- High cost (best suited when outstanding properties are required) - Requires high processing temperatures
*Polypropylene (PP)	A thermoplastic used widely in packaging, labeling and textiles among other applications. Sample applications: laboratory equipment, ropes, piping systems, plastic moldings	- Tough - Flexible - Good chemical, heat, and corrosion resistance - Good fatigue resistance - Food safe - Low-cost material	- Challenging to use in AM - Tendency to warp heavily - Has poor layer adhesion
*Acrylonitrile Styrene Acrylate (ASA)	A thermoplastic developed as an alternative to ABS with improved weather resistance. Sample applications: prototyping, gutters, drain pipes, bumper covers, sideview mirror housings.	- Strong - Rigid - Relatively easy to print - High impact strength - Good chemical resistance - Good heat resistance - Warps less than ABS - Better weather resistance than ABS - Compatible with other plastics - May be solvent-welded - Low-cost material	- Mildly hygroscopic, potentially requiring drying prior to use. - Releases toxic smoke when burned - Susceptible to concentrated inorganic acids, aromatic and chlorinated hydrocarbons, esters, ethers, ketones and some alcohols.
Thermoplastic Polyurethane (TPU)	A class of polyurethane that is elastic, transparent and resistant to oil, grease and abrasion. Sample applications: automotive instrument panels, performance films, wire and cable jacketing, hoses and tubes	- Flexible - Good abrasion resistance - Good impact resistance - Good weather resistance - Versatile - Resistant to oil and grease	- Drying is often required prior to use - Some grades of TPU have short shelf life
*Polyethylene Terephthalate Glycol-modified (PETG)	PET is a commonly used plastic often used in water bottles, clothing fibers and food containers. Sample applications: plastic bottles, flexible food packaging, thermal insulation (e.g. space blankets)	- Good middle ground between ABS and PLA. - More flexible and durable than PLA - Easier to print than ABS - High strength - High impact resistance - Temperature resistant - Minimal shrinkage/warping - Excellent layer adhesion	- Hygroscopic, requiring filaments be stored in a cool, dry environment - Scratches easily - Material properties may be weakened by UV light.
*Polyethylene (PE)	One of the most widely produced thermoplastic polymers in the world, although not a popular plastic for AM. Sample applications: Rods, trays,	- High strength-to-density ratio - Good compressive and tensile strength - Good impact strength - Good corrosion resistance - Durable	- Tends to shrink and distort easily when cooled. - Difficult to prototype with. - Does not stick together well. - Challenging to use in AM - Currently no reliable way to print with

AM Polymer**	Description	Typical Advantages	Typical Disadvantages
	pipes, containers, food boxes.	- Good machinability - Easily recyclable - Low-cost material	this material.
*Polymethyl Methacrylate (PMMA)	A thermoplastic often used as a lightweight and shatter resistant alternative to glass. Sample applications: Vehicle exterior light lenses, eyeglass lenses, bone cement, dentures	- Strong, but not as strong as PC - Good impact strength - Tough and durable - Rigid - Soluble in acetone - Compatible with human tissue - Low-cost material	- Not a commonly used AM material. - Prone to scratching - High nozzle temperature is required to prevent warping and maximum clarity. - Enclosing the AM chamber may be needed to regulate cooling.
* Polylactic acid (PLA) (Example of Environmentally Degradable Polymer (EDP))	PLA is one of the most common and user-friendly materials for FDM 3D printing along with ABS. Sample applications: Medical suturing, surgical implants, food packaging, bags.	- Harder than ABS - Environmentally friendly - Available in a wide variety of colors - Dimensionally stable, so no need for a heated bed. - Commonly used for "Lost PLA casting" applications - Non-toxic - Capable of controlled degradation rate. - Low-cost material	- Water soluble, making it a poor material choice for humid environments. - Low glass transition and melting temperatures
*Polystyrene (PS)	One of the most widely used plastics in the world, although not common as an AM material. Sample applications: protective packaging, containers, lids, bottles, trays	- Hard when cooled - Easy to use for molding and vacuum forming - Low-cost material	- Poor barrier to oxygen and water vapor - Relatively low melting point - Brittle - Slow to biodegrade
*Waxes	Wax is an organic resin. AM waxes are similar to investment-casting waxes. Sample applications: casting (metal parts), prototypes, and melt-away wax supports.	- Hydrophobic - Soluble in organic solvents - Wax pattern can be melted out as part of manufacturing process - Good accuracy and resolution	- Fragile and breaks easily in shipment - Very temperature sensitive - Brittle when exposed to cold - Typically softens above 60 deg C and melts above 80 deg C. - Slow adaption by casting industry until similarity to casting waxes is proven (i.e., low ash content and minimal thermal expansion during burnout).

A variety of methods are available for finishing, including but not limited to:

a. **Mechanical methods**
  - Media blasting, (shot-peen, bead, powder)
  - Grinding
  - Tumbling
  - Hand finishing

b. **Micro-machining Process:** A chemical reaction at the surface of the part is coupled with material removal driven by an abrasive fluid flow.

c. **Isotropic Super Finishing Process:** A finishing process making use of proprietary chemistries to form an intermediate conversion coating on the part's surface. Nonabrasive media removes the conversion coating from peaks and the conversion coating is re-formed in cycles to reach the desired surface finish.

d. **Drag Finishing:** Parts are attached to fixtures and mechanically dragged through an abrasive grinding or polishing media which deburrs and finishes.

e. **Abrasive Flow Machining:** Pressurized flow of chemically inactive, non-corrosive media containing abrasive particles applied to part. Internal passages can be smoothed with this method but part-specific tooling is required to maintain the media pressure in the gap between the part and fixture.

f. **Media Blast:** High-velocity impact of particulate media such as steel pellet (shot), sand, or powder. The media is propelled at the target surface by centrifugal force or pressurized air.

g. **Mass Finishing:** Parts in bulk are finished by a mixing action inside a container with an abrasive media. Tumbling or barrel finishing uses a horizontally mounted hexagonal or octagonal unit and a "landslide" action to mix the parts and media. Vibration grinding uses a tub in constant motion which can operate faster and with a higher capacity than tumbling.

h. **Electrochemical machining/electro polishing:** A machining tool under DC current and in the presence of an electrolyte fluid creates a reaction that removes material from the work piece.

i. **Electroplating:** A thin coating of one metal is added to the surface of another metal. The work part is set up in an electrolytic circuit so the positive ions of the coating metal are attracted to the negatively charged part.

j. **Laser re-melting/polishing:** Matter is redistributed using a laser which can fill micro-valleys and smooth micro-peaks.

k. **Thermal deburring:** A controlled mixture of gases in an enclosed chamber containing the work piece is ignited so the burrs are vaporized via combustion. Subsequent treatment is required to clean parts of residual oxides.

l. **Vapor smoothing:** A process using a solvent to melt the surface of a polymer part. The part is placed in a vapor chamber where it is exposed to the solvent and then put in cooling chamber to stop liquefaction. The cooling ensures only the surface melts and the object's shape is maintained.

m. **Solvent dipping:** A dipping process where a polymer part is placed into a solvent such as acetone. Results are similar to vapor smoothing, but it is more difficult to maintain dimensional accuracy because the solvent can act quickly and aggressively.

APPENDIX B. SOURCE DATA PREPARATION AND INSIGHTS

The purpose of this section is to sequentially outline the process of compiling all required data to feed the printability heuristic in evaluating 9B COG aviation consumable orders from INDOPACOM deployment geozone order transaction data.

To capture all the input data required for our heuristic formula, we compile a source dataset with the headings outlined in Table 27. The source data contains various continuous and dynamic characteristics for each unique record. However, for the heuristic to effectively evaluate these characteristics for printability, several additional data sources needed to be included in the source data for the model. We compiled this data from four additional sources to achieve the required heuristic input parameters and better understand each order’s continuous characteristics.

Table 27. Column Headings and Data types Required for Heuristic Input. Source: (Bui 2022) (Naval Supply Systems Command 2015) (Defence Logistics Agency 2022)

```
Data Columns (total 44 columns):
 #   Column                          Dtype
---  ------                          -----
 0   Geozone_Ordered_Description     object
 1   Document_Number                 object
 2   DoDAAC                          object
 3   Series                          object
 4   NIIN                            str64
 5   FSC                             object
 6   Quantity                        float64
 7   UI                              object
 8   Cog                             object
 9   Ordered_Date                    datetime64[ns]
 10  Entered_Date                    datetime64[ns]
 11  Issued_Date                     datetime64[ns]
 12  Shipped_Date                    datetime64[ns]
 13  Received_Date                   datetime64[ns]
 14  Source_of_Supply                object
 15  Pricd_01                        int64
 16  Ipg_01                          int64
 17  Geozone_Ordered                 int64
 18  Geozone_Received                object
 19  Is_Cancelled                    int64
 20  Is_Complete_BO                  int64
 21  Is_Pending_BO                   int64
 22  Is_Reorder                      int64
 23  Project_Code                    object
 24  Required_Delivery_Date          object
 25  Supp_Addr                       object
 26  Fund_Code                       object
 27  ADVICE_CODE                     object
 28  Est_Ship_Date                   datetime64[ns]
 29  Status                          str64
 30  Days                            int64
 31  Contract_Filled                 object
 32  DSS_CUBE                        float64
 33  DSS_WEIGHT                      float64
 34  ITEM_NAME                       object
 35  COMMON_NAME                     object
 36  PROJECT_CODE                    object
 37  REMARKS                         object
 38  PRINTPROJ                       object
 39  FSC_label                       object
 42  FSC_Print                       object
 43  CATEGORYdesc                    object
dtypes: datetime64[ns](6),float64(3), int64(8), object(25), str64(2)
```

A. SOURCE DATA CLEANING

We source the initial data from Commander, U.S. Pacific Fleet (COMPACFLT) N41B fleet supply directorate, who gather the requested transaction information with their requisition and asset visibility tool *Birdtrack* (Bui 2022), covered in Section 2, Paragraph A in this chapter. Aside from descriptive data about an individual requisition, such as document number and NSN, our heuristic needs each records U/I, order quantity, and source of supply as input parameters. These inputs are all sampled from the initial data; however, we require several additional merged datasets to compile all the required heuristic inputs.

Ensuring that only customer originated orders were considered within the data set, any requisition classified as initial outfitting, canceled orders, and transactions with a suffixes code, referring to order routed out of the INDOPACOM AOR prior to delivery, were omitted in advance of data transmission. The initial data request did not include transactions where the units local inventory stock was issued to fulfill the requirement. The data transmitted via DODSafe secure file sharing service, in the form of a Microsoft comma separated values (.CSV) file, approximately 219 Megabytes (MB) in size, with a range of 1,044,323 individual transactions. The source data contains USN requisitions from issue priority groups 1 and 2 (IPG 1 and 2) for all INDOPACOM geozones. We present the initial geozones in Table 7 from the INDOPACOM geozone location map depicted in Chapter I Figure 1.

Table 28. Initial Source Data Geozones Numbers

Geozone Ordered Description	Geozone Ordered
Deployed Central Pacific	**15**
Deployed Guam	**9**
Deployed Indian Ocean	**8**
Deployed Pacific Ocean	**7**
Deployed Sasebo	**6**
Homeport Guam	**93**
Homeport Hawaii	**96**
Homeport Sasebo Japan	**92**
Homeport Yokosuka Japan	**91**

To narrow the scope of data, we consider the force activity designator (FAD) code assigned to each record. Booth (2002) discusses in detail the Navy's procedures to set requisition priorities, including force activity and the urgency of need designators. Each unit is assigned a FAD relating to its operational status at a given time, such as deployed, surge, maintenance availability, or home-ported. A FAD is a Roman numeral designation between I and V that determines the supply priorities a unit is permitted to employ when placing new orders for material from the supply system. The requisition priority can affect an order's lead time. Entered by the Logistics Specialist placing the order, the priority denotes the criticality of required order for a pending repair action. DOD activities utilize 15 primary priority status codes. The maximum priority is "1," whereas the lowest priority is "15."

To further refine the data more in line with the research goals, records with a geozone of 92, 92, 93, or 96 were omitted, as these records originated from units in a non-deployment related FAD. The research goals indicate an analysis considering AM as an option for the most critically ordered repair parts. Therefore, we only consider orders from deployment-related FADs and geozones. Figure 17 highlights the issue priority groups (IPGs), FADs, and priority designators that remained within this research effort's scope.

Urgency of Need Designator		FAD I	FAD II	FAD III	FAD IV	FAD V
		Priority Designator				
A Unable to perform	IPG1	01	02	03	07	08
B Performance impaired	IPG2	04	05	06	09	10
C Routine		11	12	13	14	15

Figure 17. Scope of Records Considered in Source Data-Issue Priority Group 1 and 2, Priority Designators 01–06, FAD's I, II, III. Source: (Naval Supply Systems Command 2015)

We flag 829,667 unique records with errors primarily for missing values within a specific data field. However, if a record with a "*NaN*" value in the `Required Delivery`

Date, Supp Addr, or Shipped Date, the record remained within the data set as a missing continuous characteristic within one of these fields would not hamper the record's usability. We omit records with missing data within the UI, Cog, Project Code, or FSC, as these continuous characteristics are all integral to the printability heuristic.

If a missing field presents in either the Ordered Date, Shipped Date, Received Date, or a combination of more than one of these three missing date fields, we omit the record from consideration. Order lead time is a critical statistic within the simulation model; therefore, if any record did not contain a value in their respective Ordered Date field, the record is removed.

We convert all values in columns Ordered Date, Entered Date, Shipped Date, Received Date, and Est Ship date to the datetime64[ns] data type, allowing for accurate calculations involving order lead times. To achieve this, we add the new columns Days and Status to the dataframe. For this research, we consider an order delivered as long as an order has either Ordered Date and/or Entered Date serving to instantiate the order, then a date value in the Shipped Date, Received Date, or Est Ship date field. We assign orders considered delivered to the customer a value of CLOSED in the Status field. If a record contains no entry in its Shipped Date, Received Date, or Est Ship date field, the final date from the source data range, 25 April 2022, is then given to the Days field for that record, and a Status of OPEN is assigned. This indicates the requisition is still OPEN and incomplete at the end of the data period. We then populate each record's resulting values for Days and Status, equating to the amount of lead time in days.

Moving on, we include a new column Contract_Filled to identify if contracting is the source of supply for an order. We take this primary indicator from the Source_of_Supply column for each unique record and outputs into the created Contract_Filled field. The output results from a Boolean response value of YES = TRUE if Source_of_Supply = 'SMS' or 'ERP,' and a NO = FALSE if else.

These Routing Identifier Codes (RIC) codes denote the requisitioned item is either managed by Defense Logistics Agency (SMS) or NAVSUP WSS Mechanicsburg/ Philadelphia (ERP). A complete listing of RICs is found in the NAVSUP P-485 Volume II (Naval Supply Systems Command 2015).

B. SOURCE DATA INSIGHTS

From the now cleaned initial source data, we derive the following insights.

1. COG Selection

The stacked univariate histogram in Figure 18 shows the distribution and frequency of the number of orders per day for the five Cognizance Codes (COGs) with the most unique records within the source data. The 9B COG, pertaining to Navy-owned stocks of DLA Basic Sustainment Material, has a primary inventory manager of NAVSUP Weapon System Support (WSS) in Mechanicsburg, PA (Navy COGs), returned the most individual records. This large sample size made the 9B COG records the best fit for this research. This fit is primarily due to the print potential of repair parts that are inherently consumable and more simplistic as compared to complex aviation repairables.

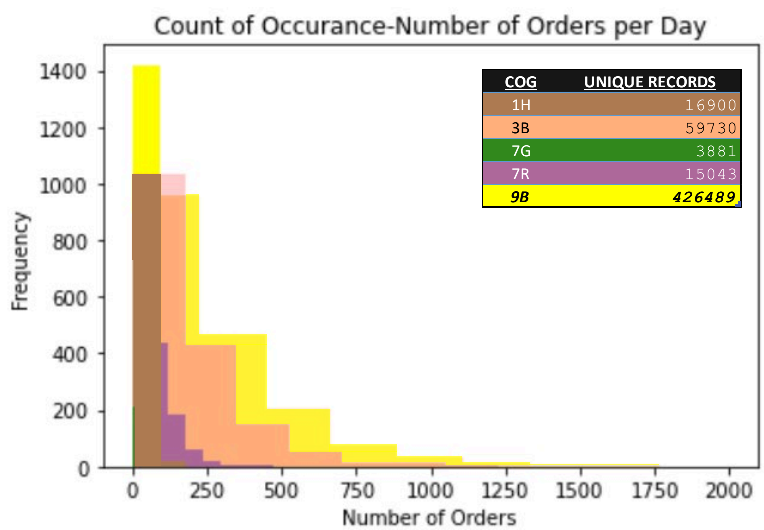

Figure 18. Top Five COGs by Number of Unique Occurrences, Grouped into Frequency of Orders per Day.

2. Date Range Rescope

The data range contained five years of transactions ordered and received by units located in one of the nine Geozones, based on where the order originated. We truncate this initial range to the period between April 1, 2019, through April 25, 2022. The rationale for this reduction is primarily due to the limited historical referencing capabilities of the *Birdtrack* tool, which can only query more detailed transaction history for three years from the present day. This reduction eliminated approximately 5% of overall 9B COG records preventing a negative skew of the results. We present a date range by quantity of orders time-series plot for the period between April 2019 through April 2022 in Figure 19.

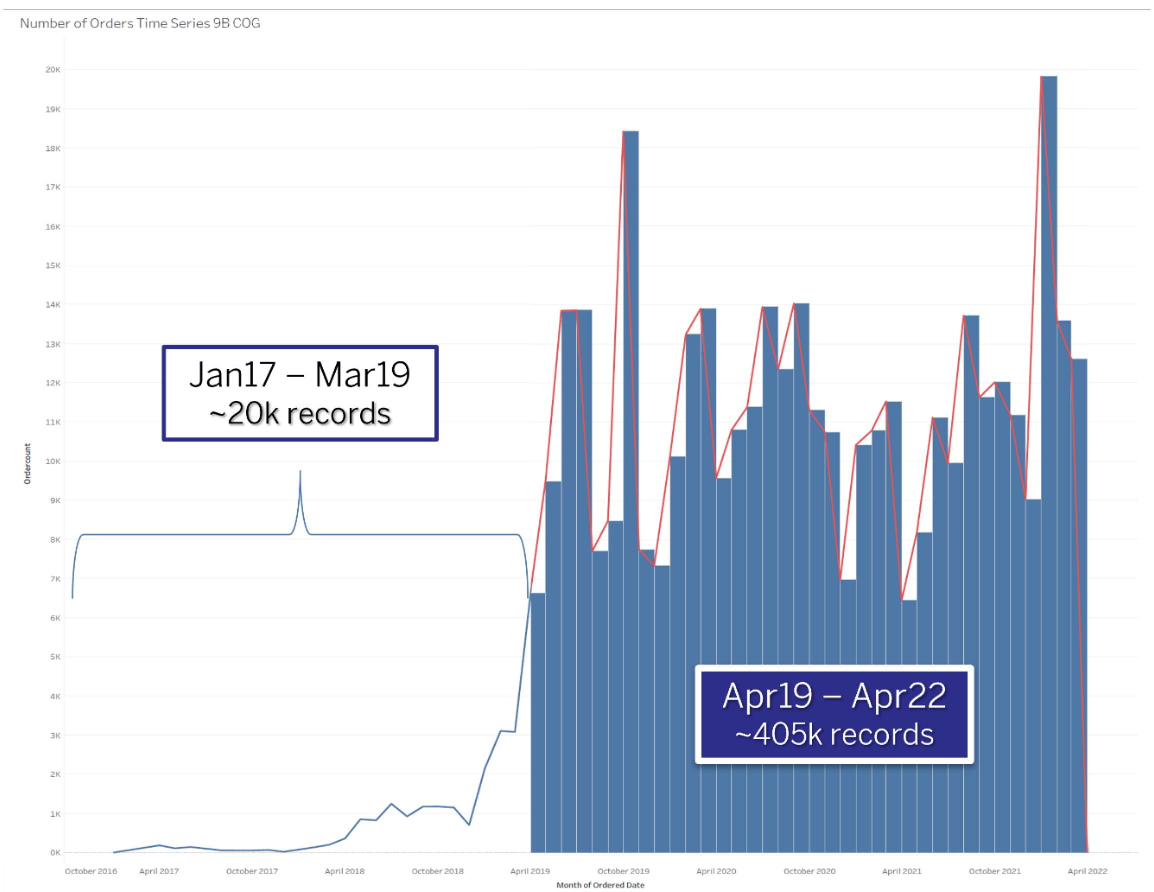

Figure 19. Cleaned Source Data Time Series Plot Number Unique 9B COG Orders Per Day, Jan17–Apr22

3. Profile of 9B Order Data

From the newly scoped 9B COG three-year data range, when plotting order homogeneity of the variance homogeneous dispersion. We observe Homoscedasticity along with a generally unbiased dispersal around the mean orders per month, shown bracketed by dashed blue lines in Figure 20. The dashed red boxes denote two outlier months within the source data as it pertains to number of orders per month. The cause of the spike in orders can be speculated, such as an additional Carrier Strike Group (CSG) within a geozone during those outlier months. However, ascertaining the exact operation posture of INDOPACOM deployed forces during these outlier timeframes would not ultimately inform the sampling objectives.

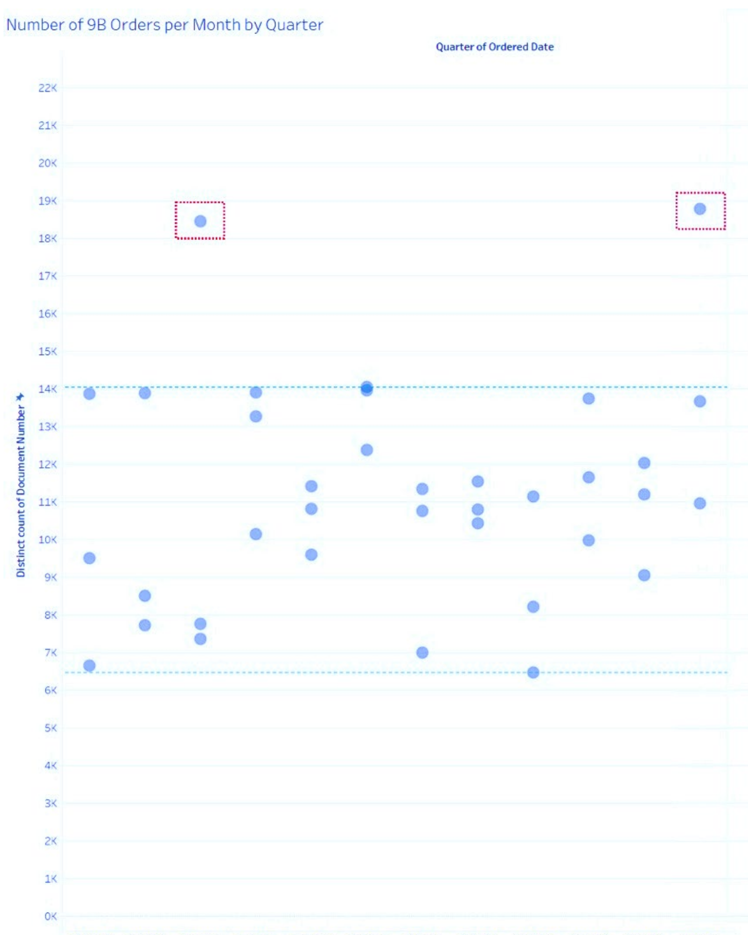

Figure 20. Plot of Number of 9B Orders Per Month by Quarter

With established source data parameters, we make an additional request to the topic sponsor for data to confirm the selection of a specific 3-year date range. To confirm this selection, the request included only 9B COG transactions from the newly focused 3-year date range, excluding transactions classified as initial outfitting of an item and cancellations. However, this requests also included orders fulfilled by a deployed unit's local inventories. These orders open and close within 24 hours, and within Figure 21, are represented by the orange-colored division in the Sankey diagram.

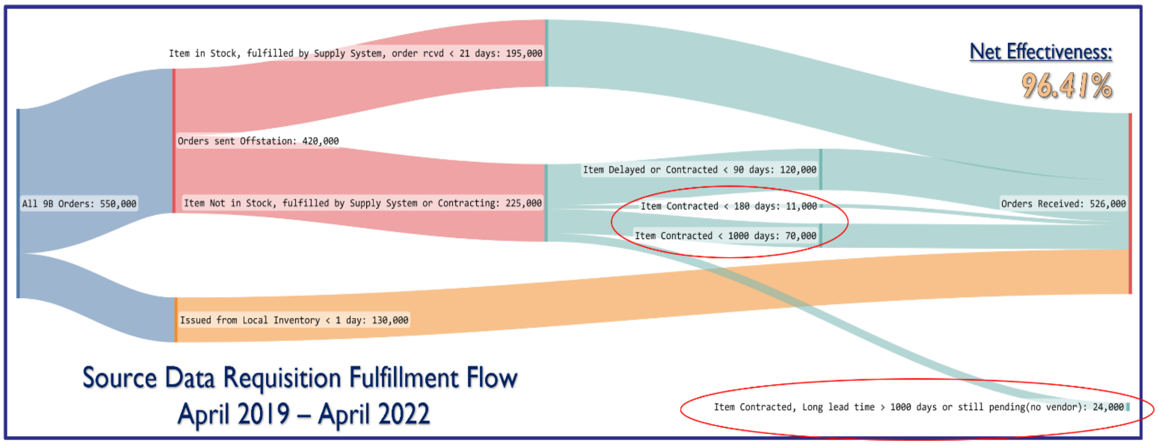

Figure 21. 9B Order Fulfillment Flow, INDOPACOM USN Deployed Units, April 2019–April 2022

Figure 21 depicts the fulfillment pathways for every 9B COG order transited to either delivery to the end user customer or remaining unfulfilled at the end of the three years. As defined in the OPNAVINST 4441.12E (2022), the net effectiveness is the "percentage of total demands received for stocked items and satisfied from stock on hand at any given echelon of inventory. We calculate net effectiveness as total repair part issues divided by the sum of repair part issues and repair part demands that are not in stock." Simply put, net effectiveness is a measured ratio of supply system performance shown in Equation 2.

$$Net\ Effectiveness = \frac{Number\ of\ Orders\ Fulfilled}{Number\ of\ Orders\ Placed} \tag{2}$$

As put forth in the 4441.12E *Retail Supply Support of Naval Activities and Operating Forces* instruction (2022), logistics response time (LRT) measures the off-station and off-ship response times, including maintenance-related direct turnover requirements and stock replenishment requisitions. LRT depends on issue priority group (IPG) and associated time-definite delivery (TDD) standards. The Navy supply system's goal is that 85% of orders achieve TDD standards. Net effectiveness measured 96.41% during these three years in the source data, well above the 85% goal. Therefore, based on the fulfillment flows in Figure 8, we aim to evaluate the characteristics and improve the lead times of the 81,000 orders that took over 180 days to fulfill while identifying those that may be strong candidates for AM.

APPENDIX C. PROJECT CODE DESCRIPTIONS

PROJECT_ CODE	REMARKS	PRINTPROJ
5	(appears less than 3 instances)	NO
10	(appears less than 3 instances)	NO
13	(appears less than 3 instances)	NO
17	(appears less than 3 instances)	NO
20	(appears less than 3 instances)	NO
21	(appears less than 3 instances)	NO
22	(appears less than 3 instances)	NO
33	(appears less than 3 instances)	NO
49	(appears less than 3 instances)	NO
71	(appears less than 3 instances)	NO
72	(appears less than 3 instances)	NO
78	(appears less than 3 instances)	NO
79	(appears less than 3 instances)	NO
58	(appears less than 3 instances)	NO
56	(appears less than 3 instances)	NO
88	(appears less than 3 instances)	NO
95	(appears less than 3 instances)	NO
98	(appears less than 3 instances)	NO
99	(appears less than 3 instances)	NO
100	(appears less than 3 instances)	NO
101	(appears less than 3 instances)	NO
119	(appears less than 3 instances)	NO
120	(appears less than 3 instances)	NO
121	(appears less than 3 instances)	NO
127	(appears less than 3 instances)	NO
132	(appears less than 3 instances)	NO
150	(appears less than 3 instances)	NO
155	(appears less than 3 instances)	NO
161	(appears less than 3 instances)	NO
164	(appears less than 3 instances)	NO
166	(appears less than 3 instances)	NO
175	(appears less than 3 instances)	NO
179	(appears less than 3 instances)	NO
189	(appears less than 3 instances)	NO
205	(appears less than 3 instances)	NO
211	(appears less than 3 instances)	NO
213	(appears less than 3 instances)	NO
215	(appears less than 3 instances)	NO
220	(appears less than 3 instances)	NO
226	(appears less than 3 instances)	NO
227	(appears less than 3 instances)	NO

235	(appears less than 3 instances)	NO
241	(appears less than 3 instances)	NO
248	(appears less than 3 instances)	NO
250	(appears less than 3 instances)	NO
259	(appears less than 3 instances)	NO
260	(appears less than 3 instances)	NO
262	(appears less than 3 instances)	NO
272	(appears less than 3 instances)	NO
293	(appears less than 3 instances)	NO
290	(appears less than 3 instances)	NO
298	(appears less than 3 instances)	NO
301	(appears less than 3 instances)	NO
312	(appears less than 3 instances)	NO
322	(appears less than 3 instances)	NO
323	(appears less than 3 instances)	NO
325	(appears less than 3 instances)	NO
335	(appears less than 3 instances)	NO
336	(appears less than 3 instances)	NO
337	(appears less than 3 instances)	NO
339	(appears less than 3 instances)	NO
340	(appears less than 3 instances)	NO
341	(appears less than 3 instances)	NO
344	(appears less than 3 instances)	NO
350	(appears less than 3 instances)	NO
362	(appears less than 3 instances)	NO
500	requisition material for ship availabilities including ship overhauls	NO
511	requisition material for ship availabilities including ship overhauls	NO
550	requisition material for ship availabilities including ship overhauls	NO
621	requisition material for ship availabilities including ship overhauls	NO
650	requisition material for ship availabilities including ship overhauls	NO
658	requisition material for ship availabilities including ship overhauls	NO
702	non-aviation NORS CASREP	NO

706	Not Mission Capable Supply West Coast	MAYBE
707	Partial Mission Capable Supply West Coast	MAYBE
711	non-aviation NORS CASREP	NO
729	non-aviation NORS CASREP	NO
730	out of reporting aircraft/SE	MAYBE
733	Non-Aviation ANMCS requisitions of Atlantic Fleet ships	NO
734	Support of Allison 501K Gas Turbine Engines	NO
740	non-aviation NORS CASREP	NO
742	Submarine Extended Operating Cycle	NO
743	Non-Aviation ANMCS Requisitions of Pacific Fleet Ships	NO
747	non-aviation NORS CASREP	NO
749	SSP FBM/SWS	NO
752	non-aviation NORS CASREP	NO
755	Replenishment of the LAMPS Mark III Pack-Up Kit (PUK)	MAYBE
756	Not Mission Capable Supply East Coast	MAYBE
757	Partial Mission Capable Supply East Coast	MAYBE
762	C2/C3 CASREP for Middle East Force Ships	NO
770	Stock Replenishment and Redistribution Orders	MAYBE
774	Pre-expended Bin Stocks	YES
777	Assigned, publication not desired	MAYBE
743	Non-Aviation ANMCS Requisitions of Pacific Fleet Ships,	NO
999	Special Requirements Code 999 identifies transactions related to critical items as requiring expedited handling	MAYBE
3AZ	DLA Disposition Services-offered assets for the purpose of wholesale procurements	NO
3FL	Established to monitor the requisitions and issues of Tamiflu	NO

55Z	requisition material for ship availabilities including ship overhauls	NO
5AK	requisition material for ship availabilities including ship overhauls	NO
5AP	requisition material for ship availabilities including ship overhauls	NO
5BK	requisition material for ship availabilities including ship overhauls	NO
5ET	requisition material for ship availabilities including ship overhauls	NO
5FO	requisition material for ship availabilities including ship overhauls	NO
5FU	requisition material for ship availabilities including ship overhauls	NO
5GC	requisition material for ship availabilities including ship overhauls	NO
5M3	requisition material for ship availabilities including ship overhauls	NO
5NB	requisition material for ship availabilities including ship overhauls	NO
5Z1	requisition material for ship availabilities including ship overhauls	NO
6AC	requisition material for ship availabilities including ship overhauls	NO
6AK	requisition material for ship availabilities including ship overhauls	NO
6AP	requisition material for ship availabilities including ship overhauls	NO
6AX	requisition material for ship availabilities including ship overhauls	NO

6BB	requisition material for ship availabilities including ship overhauls	NO
6BO	requisition material for ship availabilities including ship overhauls	NO
6CI	requisition material for ship availabilities including ship overhauls	NO
6DZ	requisition material for ship availabilities including ship overhauls	NO
6ET	requisition material for ship availabilities including ship overhauls	NO
6FF	requisition material for ship availabilities including ship overhauls	NO
6FU	requisition material for ship availabilities including ship overhauls	NO
6GE	requisition material for ship availabilities including ship overhauls	NO
6GF	requisition material for ship availabilities including ship overhauls	NO
6GJ	requisition material for ship availabilities including ship overhauls	NO
9BJ	requisition material for ship availabilities including ship overhauls	NO
9GF	Operation Enduring Freedom	NO
9GI	EUCOM Current Ops	NO
9GJ	CENTCOM Current Ops	NO
AK0	Aviation Not Mission Capable Supply	MAYBE
AK1	Aviation unscheduled repair work stoppage	MAYBE
AK7	Partial Mission Capable Supply	MAYBE
AN1	Aviation Overhaul scheduled, work stoppage	MAYBE
AP5	Normal mission consumables, clothing, dental, medical, food, fuel	MAYBE

AV6	Aircraft personnel safety equipment Roll back, mat'l turn in, no longer required	MAYBE
AW3	Aircraft Outfitting allowance, shortage	MAYBE
AZ0	aircraft Disposal program	MAYBE
B70	Aircraft Support Equipment	MAYBE
BBE	Aircraft SE range reduction	MAYBE
BBH	Aircraft SE range reduction	MAYBE
BEE	Aircraft SE COSAL replenishment	MAYBE
BEK	Aircraft SE supply system replenishment	MAYBE
BEP	Aircraft SE normal maintenance to include food, fuel, medical supplies, required to sustain operations	MAYBE
BF2	Aircraft SE range increase as operations is currently restricted	MAYBE
BHJ	Aircraft SE supply system replenishment	MAYBE
BHP	Aircraft SE normal maintenance to include food, fuel, medical supplies, required to sustain operations	MAYBE
BJK	Aircraft SE supply system replenishment	MAYBE
BK0	Partial Mission Capable Support Equipment	MAYBE
BK1	AIMD Unscheduled repair on in-use equipment resulting in work stoppage	NO
BK5	Aircraft SE unscheduled repair of in-use equipment forecasted by customer	NO
BN1	Aircraft SE overhaul work stoppage	NO
BP5	Aircraft SE normal maintenance to include food, fuel, medical supplies, required to sustain operations	NO
BPU	Aircraft SE normal maintenance to include food, fuel, medical supplies, required to support design change	NO
BW3	Aircraft SE initial outfitting allowance	NO

BZ5	Aircraft SE disposal	NO
C53	Contractor Item	NO
CFR	Contractor Item	NO
E50	Surface Ship item	NO
E53	Surface Ship item	NO
E5K	Surface Ship item	NO
E5Y	Surface Ship item	NO
E9B	Surface Ship item	NO
ED5	Surface Ship item	NO
EE0	Surface Ship item	NO
EE1	Surface Ship item	NO
EE2	Surface Ship item	NO
EE3	Surface Ship item	NO
EE4	Surface Ship item	NO
EE5	Surface Ship item	NO
EE6	Surface Ship item	NO
EE7	Surface Ship item	NO
EE8	Surface Ship item	NO
EE9	Surface Ship item	NO
EK5	Surface Ship item	NO
EP5	Surface Ship item	NO
EPS	Surface Ship item	NO
F23	SSGN Trident Sub	NO
F25	SSGN Trident Sub	NO
FK5	SSGN Trident Sub	NO
FLU	SSGN Trident Sub	NO
FP5	SSGN Trident Sub	NO
GH0	AS Sub Tender	NO
GH1	AS Sub Tender	NO
GH2	AS Sub Tender	NO
GH3	AS Sub Tender	NO
GH4	AS Sub Tender	NO
GH5	AS Sub Tender	NO
GH6	AS Sub Tender	NO
GH8	AS Sub Tender	NO
GJ0	AS Sub Tender	NO
GJ1	AS Sub Tender	NO
GJ2	AS Sub Tender	NO
GJ3	AS Sub Tender	NO
GJ4	AS Sub Tender	NO
GJ5	AS Sub Tender	NO
GJ6	AS Sub Tender	NO
GJ7	AS Sub Tender	NO
GJ8	AS Sub Tender	NO
GJ9	AS Sub Tender	NO

GK5	AS Sub Tender	NO
GP5	AS Sub Tender	NO
H5K	Supply Support Ship	NO
HE5	Supply Support Ship	NO
HH5	Supply Support Ship	NO
HJ0	Supply Support Ship	NO
HJ5	Supply Support Ship	NO
HK5	Supply Support Ship	NO
HP5	Supply Support Ship	NO
JE0	Nuclear sub (except TRIDENT)	NO
JE1	Nuclear sub (except TRIDENT)	NO
JE2	Nuclear sub (except TRIDENT)	NO
JE3	Nuclear sub (except TRIDENT)	NO
JE4	Nuclear sub (except TRIDENT)	NO
JE5	Nuclear sub (except TRIDENT)	NO
JK0	Nuclear sub (except TRIDENT)	NO
JK1	Nuclear sub (except TRIDENT)	NO
JK5	Nuclear sub (except TRIDENT)	NO
JK9	Nuclear sub (except TRIDENT)	NO
JKI	Nuclear sub (except TRIDENT)	NO
JP0	Nuclear sub (except TRIDENT)	NO
JP5	Nuclear sub (except TRIDENT)	NO
JP6	Nuclear sub (except TRIDENT)	NO
JS5	Nuclear sub (except TRIDENT)	NO
KJ5	Surface Missile Ship	NO
LA5	Other Fleet units, oceanographic	NO
LE0	Other Fleet units, oceanographic	NO
LE1	Other Fleet units, oceanographic	NO
LE4	Other Fleet units, oceanographic	NO
LE5	Other Fleet units, oceanographic	NO
LES	Other Fleet units, oceanographic	NO
LJ5	Other Fleet units, oceanographic	NO
LK1	Other Fleet units, oceanographic	NO
LK5	Other Fleet units, oceanographic	NO
LN8	Other Fleet units, oceanographic	NO
LP5	Other Fleet units, oceanographic	NO
LS5	Other Fleet units, oceanographic	NO
MK5	Shore supply facility unscheduled repair of in-use equipment, forecasted	MAYBE
MY9	Shore supply facility, misc, misc	MAYBE
N6P	Industrial Organizations,	NO
NAA	Industrial Organizations,	NO
NK1	Industrial Organizations, Aircraft Depot Allowance	MAYBE

NK5	Industrial Organizations,	NO
NP5	Industrial Organizations,	NO
NRP	Industrial Organizations, Hospital, normal ops	NO
NY9	Industrial Organizations, misc, misc	MAYBE
PFZ	CNO Special Program, increase range, marine aircraft	MAYBE
PL5	CNO Special Program, increase range, marine aircraft	MAYBE
RP5	Wholesale warehouse shore	MAYBE
RR5	Wholesale warehouse shore	MAYBE
S25	Production/manufacture	MAYBE
SC8	Production/manufacture	MAYBE
SFV	Production/manufacture	MAYBE
SN4	Production/manufacture	MAYBE
WP5	Unit/team-operational (EOD)	NO
X13	Sub SSBN	NO
X15	Sub SSBN	NO
X20	Sub SSBN	NO
X23	Sub SSBN	NO
X25	Sub SSBN	NO
XK0	Sub SSBN	NO
XK5	Sub SSBN	NO
XP5	Sub SSBN	NO
YNE	Miscellaneous—not otherwise classified, Overhaul-scheduled	NO
YNH	Miscellaneous—not otherwise classified, Overhaul-scheduled	NO
YP5	Miscellaneous—not otherwise classified, normal operations, food, clothing, etc, forecasted	NO
YP9	Miscellaneous—not otherwise classified, normal operations, food, clothing, etc, misc	NO
YSE	Miscellaneous—not otherwise classified Repair and overhaul shops (other than AIMD)	MAYBE
YY9	Miscellaneous—not otherwise classified, misc, misc	NO
Z09	(No Data)	NO
Z12	(No Data)	NO
Z4Z	AN/SPS-73 Radar	NO
Z5E	Nuclear Q Cosal Stock Replenishment	NO
Z5F	Nuclear Q Cosal DTO	NO

Z5Y	Steam and Electric Program New Construction for CVNs	NO
Z5Z	Combat Logistics Force (CFL) Navy Working Capital Fund (NWCF) Stock Replenishment	NO
Z6V	H-60 Intermediate Maintenance Concept	MAYBE
Z6Z	F/A-18 (A-D model) Intermediate Maintenance Concept (PMI-1/ PMI-2) Requirements	MAYBE
Z82	USMC Aircraft Armament Equipment	MAYBE
Z9M	MH-60R MISSION KIT PROGRAM	MAYBE
ZA9	High-time Aviation	MAYBE
ZAP	(No Data)	NO
ZC8	Awaiting Parts for Repair, Engine or major component	MAYBE
ZF5	Foreign Mil Sales to Japan, Aviation	NO
ZF7	Broad Arrow requirement (test bench down)	NO
ZFE	(No Data)	NO
ZFR	Flame Resistant Variant (FRV) Coverall	NO
ZFT	(No Data)	NO
ZH3	LAMPS Corrosion Control/POL Replenishment Requirements	MAYBE
ZH9	Request to fill initial repair	NO
ZHZ	(No Data)	NO
ZI1	Naval Branch Clinic	NO
ZI7	Advance Traceability and Control (ATAC) Redistribution Order/ Ready for issue matl shipments	MAYBE
ZJ2	AN/ASQ-228 Advanced Targeting Forward Looking Infrared (ATFLIR) PODs	MAYBE
ZJ6	NAVTELCOM Personnel Support Equipment	NO
ZJ7	LITTORAL COMBAT SHIP (LCS) Demand Reporting	NO
ZK3	Aircraft Flight/Survival Equipment	MAYBE
ZL9	Aircraft Maintenance Assist Module (MAM) Requirements	MAYBE
ZM5	LAMPS Work Stoppage	MAYBE
ZN2	fill Nuclear ?Q? COSAL Outfitting	NO

ZO9	Aircraft Service Chg. Kits—Res. Other	MAYBE
ZQ2	H-2 Armament	MAYBE
ZQ3	Non-Operational In-flight refueling 6/7 fleet	NO
ZQ9	A/C Engine Maint. Work Stoppage	MAYBE
ZRF	(No Data)	NO
ZU6	EA-6B POD Requirements	MAYBE
ZU7	EA-6B POD 1 Level Requirements	MAYBE
ZV5	V-22 Weapon System Training and Training Equipment	MAYBE
ZV6	High Pri SSN Requirements (ship by traceable means)	NO
ZV9	In-flight Refueling System (ARS—Buddy Stores)	MAYBE
ZYM	(No Data)	MAYBE

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APPENDIX D. FEDERAL SUPPLY CLASS DESCRIPTIONS

The Federal Supply Class (FSC) category descriptions encompassed in Appendix C are all FSC codes appearing in the sampled INDOPACOM deployed Naval forces 9B COG order data. The category descriptions are taken from the Federal Supply Classifications Groups and Classes Manual (2003), published by the Department of the Army.

FSC_label	FSC_Print	CATEGORYdesc
0	NO	n/a
98	NO	n/a
1005	NO	Guns, through 30mm
1010	NO	Guns, over 30mm up to 75mm Includes Breech Mechanisms; Mounts; Grenade Launchers for Integral- Cartridge Grenades, Single-Shot or Auto-Loading or Automatic-Firing.
1015	NO	Guns, 75mm through 125mm Includes Breech Mechanisms; Mounts; Rammers.
1020	NO	Guns, over 125mm through 150mm Includes Breech Mechanisms; Power Drives; Gun Shields.
1055	MAYBE	Launchers, Rocket and Pyrotechnic Includes Airborne Rocket Launchers adaptable to guided missile use. Excludes Specifically designed Airborne Guided Missile Launchers; Jettisonable Rocket Launchers; Launcher Fairings designed for specific airframes; Rifle Grenade Launchers; Grenade Launchers for Integral-Cartridge Grenades, Single-Shot or Auto-Loading or Automatic Firing.
1095	MAYBE	Miscellaneous Weapons Includes Line Throwing Guns; Catapult Guns; Bayonets; Saluting Guns; Signal Guns; Flare Guns; Barrage Balloons; Accessories, not elsewhere classifiable, for weapons in this

		group; Expendable Bomb Dispensers.
1240	MAYBE	Optical Sighting and Ranging Equipment Includes Periscopes for Submarines; Range and Height Finders; Telescopic Sights; Optical Instruments Integrated with Fire Control Equipment.
1420	MAYBE	Guided Missile Components Includes Structural Components; Components and Accessories Specially Designed for use on or with guided missiles, including Complete Gyro Mechanisms, Hydraulic Pumps, Automatic Pilot Mechanisms and Specially Designed Assemblies, and Electronic Guidance Equipment installed in missiles. Excludes Electronic Remote Guidance Equipment used to guide missiles; Solid and Liquid Propellant Units; Components of Gyro Mechanisms.
1440	MAYBE	Launchers, Guided Missile Includes Airborne and Nonairborne Guided Missile Launchers. Excludes Aircraft Launchers, Rocket Launchers.
1450	MAYBE	Guided Missile Handling and Servicing Equipment Includes Specially Designed Trucks and Trailers for use in transporting guided missiles; Specially Designed Slings, Hoists, Jacks, and Blowers; Self-propelled Vehicles and Trailers, Specially Designed for Guided Missile Handling or Servicing; Covers, Guided Missile; Conditioning Kits and Sets, Controlled Environment. Excludes Guided Missile Launchers (FSC 1440); Aircraft Handling and Servicing Equipment (FSC 1730).
1560	YES	Airframe Structural Components Note-This class includes fabricated system parts that are permanently attached or peculiar to the integral

		airframe of an aircraft, such as support structural components, spars, ribs, ailerons, stabilizers, bulkheads. Includes Flight Control Surfaces; Internal and External Auxiliary Fuel Tanks; Exhaust Systems; Pylons, Trim Tabs; Aircraft.
1610	MAYBE	Aircraft Propellers and Components Includes Aircraft Propellers; Propeller Blades, Cams, Cones, Hubs, Nuts, and Spinners; Test Clubs; Synchronizers; Power Control Units; Integral Oil Control Measures and Propeller Governors. Excludes Rotary Rudder and Rotary Wing Blades (FSC 1615).
1615	YES	Helicopter Rotor Blades, Drive Mechanisms and Components. Note-This class includes miscellaneous component parts specifically designed for, and used exclusively in, helicopter drive mechanisms and rotor blades when not specifically classified elsewhere in the FSC indexes. Includes Helicopter dynamic components and specially designed parts that transmit power from the aircraft power plant to the rotary wing and rotary rudder. Also included in this class are Rotors; Blades; Rotor Blade, Trim, Tabs; Blade Sets; Yokes; Clutches and Transmissions. Excludes Propellers (FSC 1610); Rotor Brake Systems Components (FSC 1630); Rotor Blade Hydraulic Folding System Components (FSC 1650); Hydraulic Servo System Components (FSC 1650).
1620	YES	Aircraft Landing Gear Components Includes Shock Struts and Components; Installation Elements, such as Torsion Bars, Vibration Links, Drag Struts; Landing Gear Trunions, Axles and Shimmy Dampeners; Specially designed

		hydraulic power steering system components. Excludes Mounting Braces and Mounting Plates permanently installed on aircraft (FSC 1680); Landing Wheels, Skis, and Floats (FSC 1630); Wheel Brakes and wheel brake cylinders
1630	YES	Aircraft Wheel and Brake Systems Includes Skis; Floats; Tracks; Landing Wheel Skid Detectors; Valves specifically designed for use with hydraulic or pneumatic wheel and brake systems; Helicopter Rotor Brake System Components. Excludes Landing Gear Axles (FSC 1620).
1640	YES	Aircraft Control Cable Products Note—Wire rope, with attachments or terminations and pulleys, used in aircraft control applications, will be classified in this class. Includes Wire Rope; Single Leg Wire Assemblies; Wire Strands; Control Pulleys; Turnbuckle Lock Clips and other wire rope attachments and terminations. Excludes General use Chain and Wire Rope (FSC 4010); general use Pulleys (FSC 3020); general use Miscellaneous Hardware (FSC 5340); general use Fittings for Rope, Cable and Chain (FSC 4030).
1650	YES	Aircraft Hydraulic, Vacuum, and De-icing System Components Note-This class includes only those components specifically designed for aircraft use. Includes Hydraulic and Pneumatic Accumulators, Pumps, Motors, Actuating Cylinders, and Filters; De-icing Boots; Fluid Type De-icing Pumps, Valves and Filters; Vacuum System Oil Separators; Pneumatic Pressurization Equipment other than that for pressurizing cabins and compartments.

1660	YES	Aircraft Air Conditioning, Heating, and Pressurizing Equipment Note- This class includes components specifically designed for use in aircraft air conditioning, heating, and pressurizing equipment. Also included are specially designed components of oxygen breathing systems used in aircraft. Includes Cabin Supercharging Equipment; Canisters; Cylinder Assemblies; Masks; Fixed Oxygen System; Specially Designed Aircraft Valves; Cabin Pressure Regulators; Heat Exchangers; Air Expansion Turbines; Aircraft Heaters; Ventilating System Components; Air Conditioning and Heating Duct Assemblies; Thermal De-icing Equipment; Cabin and Compartment Pressurizing Equipment; Air Diffusers; Cabin Pressure Selectors; Liquid Oxygen Converters.
1670	MAYBE	Parachutes; Aerial Pick Up, Delivery, Recovery Systems; and Cargo Tie Down Equipment Note- Includes specifically designed items, sets, and systems for air-to-air, air-to-surface, and surface-to-air delivery, pick up, and recovery operations, unless parts, attachments, assemblies, for use in or on such systems (i.e., space vehicle aerial recovery systems) are specifically indexed to other classes of the FSC (i.e., Transmitting Radio Buoys and Direction Finding Subsystem Components).
1680	YES	Miscellaneous Aircraft Accessories and Components Includes Control Assemblies, Push-Pull; Brace, Positioning Cargo Ramp stowed on board; Cockpit Mounted Control Quadrants; Actuators, Electro-Mechanical and Mechanical; Ventilators; Relief Tubes; Map

		Holders; Aerial Glider Towing Accessories attached to Aircraft; Belts, Safety and Lap; Harness, Shoulder and Safety; Litter Attaching Supports- ;Electric Windshield Wipers; Aircraft Onboard Inert Gas Generators; Aircraft Furniture; Aircraft Mounted Winches and Hoists; In-Flight Refueling System Components, including Fuel Components; Aircraft Curtains; Cable Tension Regulators; Sun Visors; Rear-View Mirrors; Mechanical Transmissions, Gearboxes and Constant Speed drives Specially designed for aircraft.
1710	MAYBE	Aircraft Landing Equipment. Includes Aircraft Arresting Barriers.
1730	MAYBE	Aircraft Ground Servicing Equipment Includes Energizers; Engine Preheaters; Mooring Assemblies; Wheel Chocks; Beaching Equipment; Aileron, Elevator, and Rudder Locks; Passenger Loading Ramps; Maintenance Platforms; Aircraft Maintenance and Boarding Ladders; Aircraft Maintenance Slings and Hoists; Aircraft Fin Tilting Jacks; Airfield Specialized Lift Trucks and Trailers; Fitted Covers for Airframe Components; Aircraft Engine Covers. Excludes Airfield Specialized Trucks and
1740	MAYBE	Airfield Specialized Trucks and Trailers Note-This class excludes !vehicular components! such as those listed under FSC?s 2520, 2530, and 2590. Includes Airfield Specialized Trucks and Trailers designed primarily for transporting aircraft assemblies; Trailers: Afterburner, Engine, Propeller, Fuselage, and Wing; Trucks, Aircraft Fuselage and Aircraft Wing; Skids,

		Engine Transport; Stands, Engine Transport; Bomb Trailers, Airfield; Trucks, Crashed Aircraft Removing.
2010	MAYBE	Ship and Boat Propulsion Components Includes Propulsion Shafts, Ship Propellers. Marine Transmissions, Reverse and Reduction Gear Type.
2030	MAYBE	Deck Machinery Includes Steering Gears and Controls; Boat Davits
2040	MAYBE	Marine Hardware and Hull Items Includes Anchors; Grapnels; Sea Anchors; Watertight Doors; Ship Ventilators; Hatches; Manholes; Scuttles; Airports; Fenders; Sea Chests; Scuppers; Rudders
2090	MAYBE	Miscellaneous Ship and Marine Equipment Includes Sails; Chain Ladders; Rope Ladders; Marine Furniture.
2510	YES	Vehicular Cab, Body, and Frame Structural Components Includes Leaf Type Vehicular Springs; Suspension Type Shock Absorber
2520	YES	Vehicular Power Transmission Components Includes Transfer Transmission Assemblies; Clutch Assemblies; Universal Joints; Propeller Shafts; Automotive Torque Converters; Power Takeoffs.
2530	YES	Vehicular Brake, Steering, Axle, Wheel, and Track Components. Includes Turrent Brakes, Clutch Brakes, Tank Turret.
2540	YES	Vehicular Furniture and Accessories Includes Automobile Seat Covers; Shock Absorbers; Bumpers; Windshield Wipers; Bumper Guards; Mirrors, Rear View and Side View; Vehicle Heaters.
2590	YES	Miscellaneous Vehicular Components Includes Attachments for Tanks, Self-propelled Weapons, and High-Speed Tractors; A-frames and Winches specifically designed

		for truck mounting; Cranes and Crane Booms for Wrecker Trucks
2610	MAYBE	Tires and Tubes, Pneumatic, Non-Aircraft
2620	MAYBE	Tires and Tubes, Pneumatic, Aircraft
2640	MAYBE	Tire Rebuilding and Tire and Tube Repair Materials Includes Tread Gum; Cold Patches; Friction Cord Fabric; Vulcanizing Patches; Padding Stock; Quick-Cure Gum; Tire and Tube Repair Kits; Camelback; Valves; Valve Cores.
2805	MAYBE	Gasoline Reciprocating Engines, Except Aircraft; and Components Includes Gas Reciprocating Engines; All Gasoline Reciprocating Engines except Aircraft Prime Moving.
2810	MAYBE	Gasoline Reciprocating Engines, Aircraft Prime Mover; and Components Note Engines and components classified in this FSC must be designed specifically for use as/on an aircraft prime mover. Auxiliary engines and their components will be classified in the appropriate FSC elsewhere in FSG 28. Includes Complete Engine Assemblies; Piston Rings; Cylinders; Pistons; Camshafts; Crankshafts.
2835	MAYBE	Gas Turbines and Jet Engines; Non-Aircraft Prime Mover, Aircraft Non-Prime Mover, and Components Note Engines and Components classified in this FSC are primarily for use on non-aircraft prime mover (e.g., Naval ship applications), aircraft non-prime mover (e.g., airframe mounted auxiliary power units), and for aircraft ground support equipment (e.g., start carts).
2840	MAYBE	Gas Turbines and Jet Engines, Aircraft, Prime Moving; and Components Note Engines and Components classified in this FSC

		are intended for use as/on aircraft and/or guided missile prime movers. Includes Compressor and Turbine Rotors; Blades; Combustion Chamber; Accessory Gear Box; Afterburner; Exhaust Cone; Reservoirs, Hydraulic; Tank, Oil.
2910	YES	Engine Fuel System Components, Nonaircraft Includes Carburetors; Fuel Pumps; Engine Fuel Filters; Fuel Tanks; Components for all engines except Aircraft and Guided Missile Prime Moving.
2915	YES	Engine Fuel System Components, Aircraft and Missile Prime Movers Note Fuel components specially designed for propulsion fuel systems, aircraft and missiles are to be placed in this FSC. Includes Carburetors; Fuel Pumps; Engine Fuel Filters; Fuel Controls, Jet Engine; Fuel Primers; Water Injection Controls and Valves; Fuel Valves Fuel Flow Regulators; Components of Smoke Abatement Systems.
2920	YES	Engine Electrical System Components, Nonaircraft Includes Generators; Magnetos; Spark Plugs; Ignition Coils; Ignition Distributors; Engine Voltage Regulators; Ignition Har ness Assemblies; Starting Motors for Engines.
2925	YES	Engine Electrical System Components, Aircraft Prime Moving Note Items designed for specific use on aircraft and guided missile prime movers are to be placed in this FSC. Includes Magnetos; Igniters (Spark Plugs); Ignition Coils; Ignition Distributors; Engine Voltage Regulators; Ignition Harness Assemblies; Starting Motors for Engines; Engine Accessory Generators.

2930	YES	Engine Cooling System Components, Nonaircraft Includes Cooling Fans; Radiators; Water Pumps; Water Hose Assemblies; Engine Coolant Filters; Components for all Engines except Aircraft and Guided Missile Prime Moving.
2935	YES	Engine System Cooling Components, Aircraft Prime Moving Note This class includes only cooling system components for aircraft and/or guided missile prime movers only. Includes Radiators; Cooling System Pumps; Water Hose Assemblies; Lubricating Oil Coolers and Control Valves; Oil Temperature Regulators.
2940	MAYBE	Engine Air and Oil Filters, Strainers, and Cleaners, Nonaircraft Includes Components for all Engines except Aircraft and Guided Missile Prime Moving.
2945	MAYBE	Engine Air and Oil Filters, Cleaners, Aircraft Prime Moving Note Items placed in this FSC should be specifically designed for use on aircraft or guided missile prime movers only. Includes Air Filters; Oil Filters; Strainers; Cleaners.
2990	YES	Miscellaneous Engine Accessories, Nonaircraft Includes Engine Dynafocal Suspension Mounts; Engine Driven Superchargers (not integrated with engine); Starter Cranks; Engine Starter Ropes; Exhaust Mufflers; Hand Inertia Starters; Air Duck Heaters; Engine Governors; Intake Mufflers; Combustion Type Starters; Miscellaneous Accessories for all Engines except Aircraft and Guided Missile Prime Moving.
2995	YES	Miscellaneous Engine Accessories, Aircraft Note Items classified in this class must be specifically designed

		for use with aircraft or guided missile prime movers only. Includes Engine Dynafocal Suspension Mounts; Engine Cowling Mounts; Engine Mounted Control Assemblies; Pneumatic Starters; Push-Pull Control Assemblies; Specially designed Jet Engine Air, Oil, Anti-icing and Hydraulic Regulators; Valves and Pumps; Starting Units.
3010	YES	Torque Converters and Speed Changers Includes Fluid Couplings; Nonvehicular Clutches and Couplings; Horizontal Right Angle Drive Gear Units.
3020	YES	Gears, Pulleys, Sprockets, and Transmission Chain Includes Power Transmission Chain, Matched Gear Sets.
3030	YES	Belting, Drive Belts, Fan Belts, and Accessories Includes Belt Lacings, Belt Pins.
3040	YES	Miscellaneous Power Transmission Equipment Includes Shafts and Shafting; Collars; Gearshafts; Ball Joints; Actuating Cylinders.
3110	YES	Bearings, Antifriction, Unmounted Note This class includes bearings that generally have roller or balls confined by an inner and outer ring to relieve friction in/on/around rotating/moving mechanisms. Includes Ball Bearings; Roller Bearings; Balls; Races.
3120	YES	Bearings, Plain, Unmounted Note Bearings in this class are generally one piece that retain and position moving and/or rotating parts. They may have lubrication grooves/ fittings/facilities or include pre-lubrication. Includes Sleeve Bearings; Split Bearings; Washer Type Bearings; Jewel Bearings.
3130	YES	Bearings, Mounted Note This class includes bearings that generally

		have roller or balls confined by an inner and outer ring to relieve friction in/on/around rotating/ moving mechanisms. Includes Pillow Block Units; Cartridge Units; Flange Units; Take-up Units; Hanger Box Units; Flat Box Units; Step Box Units.
3220	NO	Woodworking Machines Includes Mortisers; Tenoners; Veneer Lathes.
3417	NO	Milling Machines
3431	NO	Electric Arc Welding Equipment Includes Gas Shielded Arc Welding Machines; Arc Bonding Machines; Semi- Automatic and Automatic Arc Welding Machines.
3439	NO	Miscellaneous Welding, Soldering, and Brazing Supplies and Accessories Includes Soldering Irons; Welding Electrodes and Rods; Brazing Fluxes; Soldering Fluxes; Solder.
3455	YES	Cutting Tools for Machine Tools Includes Broaches; Files; Milling Cutters; Reamers; Saws.
3456	YES	Cutting and Forming Tools for Secondary Metalworking Machinery
3460	YES	Machine Tool accessories
3465	YES	Production Jigs, Fixtures, and Templates
3530	MAYBE	Industrial Sewing Machines and Mobile Textile Repair Shops
3655	MAYBE	Gas Generating and Dispensing Systems, Fixed or Mobile
3895	MAYBE	Miscellaneous Construction Equipment Includes Asphalt Elevators; Asphalt Heaters; Asphalt Kettles; Asphalt Transfer Equipment; Batching Plants; Stabilizing and Compacting Equipment; Concrete Mixers (All Types); Concrete Vibrators; Bituminous and Concrete Pavers; Asphalt Distributors; Sheepfoot

		Rollers; Rooters; Rippers; Pile Drivers; Bitumen Heaters; Cable Laying, Lashing, Spinning, and Reeling Equipment.
3940	YES	Blocks, Tackle, Rigging, and Slings
3950	YES	Winches, Hoists, Cranes, and Derricks Includes Windlasses: Capstans: Ore Bridges: Gypsies: Warehouse Cranes: Wharf Cranes, Mobile or Fixed: Overhead Traveling Cranes.
3990	YES	Miscellaneous Materials Handling Equipment Includes Skids, Pallets.
4010	NO	Chain and Wire Rope
4020	NO	Fiber Rope, Cordage, and Twine
4030	YES	Fittings for Rope, Cable, and Chain
4110	MAYBE	Refrigeration Equipment
4120	MAYBE	Air Conditioning Equipment
4130	YES	Refrigeration and Air Conditioning Components, including heat exchangers
4140	YES	Fans, Air Circulators, and Blower Equipment
4210	MAYBE	Fire Fighting Equipment Includes Fire Extinguishers; Fire Axes; Fire Rakes; Fire Beaters; Fire Trucks; Fire Hose; Play Pipes; Hose Fittings having one or more Fire Hose End Connections; Fire Hose Reels; Fire Fighting Trailers; Fire Hydrants; Sprinkler Heads.
4220	MAYBE	Marine Lifesaving and Diving Equipment Includes Diving and Salvage Apparatus, including Pressurized Divers? Suits; Rescue Nets, Buoyant; Inflatable Life Vests; Life Rafts.
4235	NO	Hazardous Material Spill Containment and Clean-up Equipment and Material Includes Secondary Spill Containment Sumps; Liquid Spill Containment Pallets; Spill Containment Basins; Spill Containment Systems; Absorbent, Sorbent and Blotting Materials.

4240	MAYBE	Safety and Rescue Equipment Includes Portable Fire Escapes; Safety Nets, Nonbuoyant.
4310	MAYBE	Compressors and Vacuum Pumps Includes Truck Mounted and Trailer Mounted Compressors.
4320	YES	Power and Hand Pumps
4330	YES	Centrifugal, Separators, and Pressure and Vacuum Filters
4430	NO	Industrial Furnaces, Kilns, Lehrs, and Ovens Includes Crucible Furnaces, Cupola Furnaces.
4440	MAYBE	Driers, Dehydrators, and Anhydrators Includes Evaporators.
4460	MAYBE	Air Purification Equipment Includes Electronic Precipitators, Dust Collection Equipment.
4510	YES	Plumbing Fixtures and Accessories Includes Bathtubs; Commodes; Lavatories; Shower Cabinets; Sinks; Water Closets; Accessories and Component Parts, such as Dispensers, Faucets, Holders, Racks, Shower Heads, Flush Valves and Stop Valves.
4520	MAYBE	Space and Water Heating Equipment Includes Boilers, 15 pounds WSP and under
4540	MAYBE	Waste Disposal Equipment Includes Compactors; Destructors; Garbage Disposals; Incinerators; Septic Tanks.
4710	YES	Pipe, Tube and Rigid Tubing Includes Culvert Pipes; Culvert Pipe Connector Bands; Metallic Pipes; Plastic Pipes; Tubes and Rigid Tubing and their assemblies.
4720	YES	Hose and Flexible Tubing Includes Air Duct, Metallic, Nonmetallic, and Textile Fiber Hoses and their assemblies, Flexible Tubing and their assemblies.
4730	YES	Hose, Pipe, Tube, Lubrication, and Railing Fittings Includes Adapters; Bends; Caps; Clamps; Connectors; Couplings; Crosses; Elbows;

		Expansion Joints; Ferrules; Flanges; Laterals; Lubrication Fittings; Manifolds; Nipples; Nozzles; Outlets; Plugs; Reducers; Swing and Swivel Joints; Tees; Traps; Unions; Yes.
4810	MAYBE	Valves, Powered Includes Electric Motor Operated Valves; Hydraulic Operated Valves; Solenoid Operated Valves.
4820	YES	Valves, Nonpowered Includes Automatic Nonpowered Valves; Gate, Globe, Angle, Check, and Relief Valves; Cocks.
4910	MAYBE	Motor Vehicle Maintenance and Repair Shop Specialized Equipment Includes Automotive Lifts; Wheel Aligners; Brake Service Equipment; Tire Maintenance and Repair Equipment; Test stands, and test equipment specially designed for use with motor vehicles.
4920	MAYBE	Aircraft Maintenance and Repair Shop Specialized Equipment Includes Maintenance stands designed for support of aircraft assemblies during repair or overhaul; Test Stands and Test Equipment specially designed for maintenance and repair of aircraft components such as: engines, generators, hydraulic systems, armament, automatic pilot, fire control, flight control, and navigational systems.
4921	MAYBE	Torpedo Maintenance, Repair, and Checkout Specialized Equipment Includes Specially designed maintenance, test, checkout, and repair shop specialized equipment for maintenance and repair of torpedoes, torpedo components; adapters, fixtures, inspection and holding fixtures, leveling jack assemblies, fuel filling and syphon assemblies, control surface adapter

		and protractor assemblies, afterbody cradle adapter and tilting mount assemblies, pressure air heater assemblies, motor drier and puller assemblies, test stand levels and stands for overhaul, maintenance, test, checkout, and repair of torpedo and torpedo components, test panels, fixtures, and test sets for electrical circuits, firing circuits and torpedo test sets.
4925	MAYBE	Ammunition Maintenance, Repair, and Checkout Specialized Equipment Includes Specially designed maintenance, test, checkout, and repair shop specialized equipment, for maintenance and repair of ammunition items; adapters, ammunition feeders and hoppers; inspection and holding fixtures; linkers, linkers delinkers, and delinkers to assemble and disassemble ammunition belts; surveillance ovens; explosimeters; primer firing device fixtures; mandrels; repositioning machines; gas bomb service kits; test fixtures; panels; plug assemblies; and test sets for ammunition maintenance, checkout and repair.
4930	MAYBE	Lubrication and Fuel Dispensing Equipment Includes Hand Grease Guns; Centralized Lubrication Systems; Hydrostatic Lubricators; Oil and Gasoline Dispensing Pumps; Fuel Oil Dispensing Pumps; Hand Oilers; Grease Dispensers; Pressure Gun Attachments; Sight Feed Lubricators.
4933	MAYBE	Weapons Maintenance and Repair Shop Specialized Equipment Includes Maintenance Stands, Fixtures, and Jigs.
4935	MAYBE	Guided Missile Maintenance, Repair, and Checkout Specialized Equipment Includes Checkout

		equipment and test equipment specially designed for use with guided missiles and guided missile remote control systems.
4940	MAYBE	Miscellaneous Maintenance and Repair Shop Specialized Equipment Includes Paint Spraying Equipment.
5110	YES	Hand Tools, Edged, Nonpowered Includes Chisels; Files; Pipe Cutters; Rasps; Saws; Screw Plates; Axes; Hatchets; Machetes.
5120	YES	Hand Tools, Nonedged, Nonpowered Includes Hammers; Picks; Pliers, except pliers for cutting only; Screwdrivers; Shovels; Construction Rakes, Forks and Hoes; Jacks, including Contractors? Jacks; Wrecking Bars; Glue Pots; Blowtorches.
5133	YES	Drill Bits, Counterbores, and Countersinks: Hand and Machine
5135	YES	Taps, Dies, and Collets; Hand and Machine
5180	YES	Sets, Kits, and Outfits of Hand Tools
5210	MAYBE	Measuring Tools, Craftsmen's Includes Calipers; Levels; Micrometers; Plumb Bobs; Precision Tapes; Squares; Angle Gages; Center Gages; Depth Gages; Draw Gages; Drill Point Gages; Fillet and Radius Gages; Glaziers? Gages; Height Gages (Vernier); Planer Gages; Rivet Selector Gages; Saw Tooth Set Gages; Screw Pitch Gages; Surface Gages; Telescoping Gages; Thickness Gages; Tube Bead Gages; Tube Flare Gages; Twist Drill Gages; Twist Drill and Rod Gages; Twist Drill and Tap Gages; Taper-Wire-Thickness Gages; Wire Gages; Tool Setting Planer and Shaper Gages; Gage Blocks.
5220	MAYBE	Inspection Gages and Precision Layout Tools Note-Special inspection gages are included in this class. Includes Go and Not-Go

		Gages, including Plug, Ring, Snap, Thread, and Length Gages; Profile Gages; Fixture Gages; Special Inspection Gages.
5305	YES	Screws
5306	YES	Bolts
5307	YES	Studs
5310	YES	Nuts and Washers
5315	YES	Nails, Machine Keys, and Pins
5320	YES	Rivets
5325	YES	Fastening Devices Includes Eyelets; Grommets; Aircraft Cowling Fasteners; Textile Fasteners; Retaining Rings; Threaded Inserts.
5330	YES	Packing and Gasket Materials
5331	YES	O-Ring
5335	YES	Metal Screening Includes Insect Screening; Industrial Metal Cloth; Industrial Metal Mesh.
5340	YES	Hardware, Commercial Includes Access Covers; Bumpers; Casters; Cabinet and Door Hardware; Clevises; Hinges; Latches; Straps and Strapping; Turnbuckles; Webbed Straps.
5342	YES	Hardware, Weapon System Includes Adapters; Anchor Plates and Straps Anodes, Bellows, Couplings, Control Rods; Access Doors; Fairleads; Mounts; Tie Rods; Yokes.
5355	YES	Knobs and Pointers Includes Knobs, including Calibrated Knobs, Dials, Scale.
5360	YES	Coil, Flat, Leaf, and Wire Springs
5365	YES	Bushings, Rings, Shims, and Spacers
5411	NO	Rigid Wall Shelters Includes Expandable and nonexpandable shelters.
5640	NO	Wallboard, Building Paper, and Thermal Insulation Materials Includes Paper Building Board; Ceiling Board; Gypsum Board; Insulating Board; Plasterboard; Soundproofing Board; Tar Paper;

		Wallpaper; Mineral Wool; Glass Wool Batts; Pipe Covering.
5670	YES	Building Components, Prefabricated Note-Items specified as wooden are classified in 5520 Includes Door Frames; Window Frames; Window Sashes; Eave Troughs (Gutters); Gratings; Grilles; Shutters; Fixed Fire Escapes; Mounted Partitions.
5680	YES	Miscellaneous Construction Materials Includes Expanded Metal Lath; Airplane Landing Mats; Traction Mats.
5805	MAYBE	Telephone and Telegraph Equipment
5810	MAYBE	Communications Security Equipment and Components
5831	MAYBE	Intercommunication and Public Address Systems, Airborne
5836	MAYBE	Video Recording and Reproducing Equipment
5840	MAYBE	Radar Equipment, Except Airborne
5841	MAYBE	Airborne radar equipment
5845	MAYBE	Underwater sound equipment
5850	MAYBE	Visible and Invisible Light Communication Equipment
5855	MAYBE	Night Vision Equipment, Emitted and Reflected Radiation
5860	MAYBE	Stimulated Coherent Radiation Devices, Components, and Accessories
5865	MAYBE	Electronic Countermeasures, Counter-Countermeasures and Quick Reaction Capability Equipment
5895	MAYBE	Miscellaneous Communication Equipment
5905	MAYBE	Resistors Includes Varistors; Resistive ballast Tubes; Rheostats; Resistor Networks; Resistor Mounting Hardware; Thermistors.
5910	MAYBE	Capacitors Includes Interference Filter Capacitors; Capacitor Mounting Hardware
5915	MAYBE	Filters and Networks

5920	MAYBE	Fuses, Arrestors, Absorbers, and Protectors Includes Fuseholders; Fuse Boxes; Fuse Posts; Fuse Links; Fuse Blocks; Current Limiters; Corona Balls; Electrostatic Dischargers.
5925	MAYBE	Circuit Breakers
5930	MAYBE	Switches Includes Rotary, Knife, Toggle, Push Button, Mercury, Thermostatic, and Differential Pressure Switches.
5935	MAYBE	Connectors, Electrical Includes Plugs; Jacks; Receptacles, Electronic Component Sockets and Associated Accessories
5940	MAYBE	Lugs, Terminals, and Terminal Strips Includes Binding Posts; Battery Clips; Stud Terminals; Test Clips.
5945	MAYBE	Relays and Solenoids Includes Electromagnetic Actuators
5950	MAYBE	Coils and Transformers Includes Coils, except ignition and magneto; coil assemblies; magnetic amplifiers; reactors; transformers.
5961	MAYBE	Semiconductor Devices and Associated Hardware Includes Semiconductor Assemblies; Semiconductor Diodes; Semiconductor Rectifiers, Semiconductor Thyristors; Transistors; Unitized Semiconductors; Associated Hardware except Sockets.
5962	MAYBE	Microcircuits, Electronic, Integrated Circuit Devices; Integrated Circuit Modules, Integrated Electronic Devices: Hybrid, Magnetic, Molecular, Opto-Electronic, and Thin Film.
5963	MAYBE	Electronic Modules
5965	MAYBE	Headsets, Handsets, Microphones and Speakers
5970	YES	Electrical Insulators and Insulating Materials Includes Tube, Knob, Cleat, Strain, and Standoff

		Insulators; Feed Thru Insulators; Bead Insulators; Varnish Cambric Tape; Friction Tape.
5975	YES	Electrical Hardware and Supplies Includes Conduit; Raceways; Face Plates; Condulets; Outlet and Junction Boxes; Pole Line Hardware, not elsewhere classifiable
5977	YES	Electrical Contact Brushes and Electrodes Includes Brushes for electrical rotating equipment; Carbon Stock for Brushes; Brush Arm and Holders; Lighting Electrodes.
5980	MAYBE	Optoelectronic Devices and Associated Hardware Includes Optoelectronic devices and assemblies which display numeric, alphanumeric, symbolic, or graphic information, emitters, and nondisplay optoelectronic devices
5985	MAYBE	Antennas, Waveguides, and Related Equipment Includes Aerials; Masts; Tower Equipment; Attenuators; Couplers; Transmission Lines.
5990	YES	Synchros and Resolvers
5995	YES	Cable, Cord, and Wire Assemblies: Communication Equipment
5996	MAYBE	Amplifiers Includes Audio Amplifiers, Complementary Amplifiers, Amplifiers, Operational Amplifiers, Power Amplifiers, Radio Frequency Amplifiers, Signal Amplifiers, and Video Amplifiers.
5998	MAYBE	Electrical and Electronic assemblies, Boards, Cards, and Associated Hardware
5999	MAYBE	Miscellaneous Electrical and Electronic Components Includes Permanent Magnets and Magnetostriction Elements, Caps, Clips, and Contacts, Electrical.
6020	MAYBE	Fiber Optic Cable Assemblies and Harnesses

6035	MAYBE	Fiber Optic Light Transfer and Image Transfer Devices
6060	MAYBE	Fiber Optic Interconnectors
6070	MAYBE	Fiber Optic Accessories and Supplies
6080	MAYBE	Fiber Optic Kits and Sets
6105	MAYBE	Motors, Electrical
6110	MAYBE	Electrical Control Equipment Includes Contactors; Motor Controllers; Power Servomechanisms; Switchgear; Voltage Regulators.
6115	MAYBE	Generators and Generator Sets, Electrical Includes Engine, Turbine, Wind, and Hand Driven Generator Sets and Auxiliary Aircraft Generators.
6120	NO	Transformers: Distribution and Power Station Note This class includes transformers with a kilovolt-ampere rating above 1 kva
6125	NO	Converters, Electrical, Rotating, Complete Battery Charging Equipment, Rotating; Dynamotors; Motor-Converters; Motor-Generator Sets; Phase Converters; Rotating Equipment; Synchronous Converters.
6130	NO	Converters, Electrical, Nonrotating, Complete Battery Charging Equipment, Nonrotating; Power Supplies, Multiapplication.
6135	NO	Batteries, nonRechargeable
6140	NO	Batteries, Rechargeable Includes Rechargeable Cells and Batteries.
6145	NO	Wire and Cable, Electrical BULK
6150	MAYBE	Miscellaneous Electric Power and Distribution Equipment Includes Appliance and Extension Cords; Electric Power and Distribution Cable with Attachments, Multiapplication; Common Components of Electrical Rotating Equipment, such as End Bells and Frames.

6160	YES	Miscellaneous Battery Retaining Fixtures and Liners Includes Battery Boxes, Covers, Liners, Racks, Retainers, and Trays.
6210	YES	Indoor and Outdoor Electric Lighting Fixtures Includes Airport, Railroad Platform, Stadium, and Street Lighting Fixtures.
6220	MAYBE	Electric Vehicular Lights and Fixtures Includes Automotive, Marine, Railroad, and Aircraft Lights and Fixtures.
6230	MAYBE	Electric Portable and Hand Lighting Equipment Includes Floodlights; Searchlights; Extension Lights.
6240	MAYBE	Electric Lamps Includes Fluorescent Lamps; Incandescent Lamps, Large and Miniature; Mercury Lamps; Sodium Lamps.
6250	MAYBE	Ballasts, Lampholders, and Starters
6260	YES	Nonelectrical Lighting Fixtures Includes Lanterns, Nonelectrical; Hand and Portable Carbide Lamps; Candles.
6340	MAYBE	Aircraft Alarm and Signal Systems Includes Oxygen Pressure Signals and Warning Devices, such as Air Pressure Warning Signals, Aircraft Crew Warning Signals, Altitude Warning Signals, Alarm Controls, Audible Landing Gear Alarms.
6350	MAYBE	Miscellaneous Alarm, Signal, and Security Detection Systems Includes Anti-intrusion Alarm Systems; Foghorns; Gongs; Chimes; Bells; Burglar Alarm Systems; Fire Alarms; Police Alarm Systems; Sounding Devices; Manual Gas Alarms; Landing Wands.
6505	NO	Drugs and Biologicals
6510	NO	Surgical Dressing Materials Includes Bandages, Compresses, Dressings, Gauze, Pads, Sponges, and impregnated surgical dressing materials

6515	YES	Medical and Surgical Instruments, Equipment, and Supplies Includes Anesthesia Apparatus; Blood Transfusion Apparatus; Oxygen Therapy
6520	YES	Dental Instruments, Equipment, and Supplies Includes Dental Engines; Dental Laboratory Equipment; Operating Chairs; Orthodontic Appliances; Teeth; Dental Metals; Dental
6530	MAYBE	Hospital Furniture, Equipment, Utensils, and Supplies Includes Orthopedic Equipment; Operating Lights; Physiotherapy Equipment; Sterilizers; Wheelchairs; Litters; Hospital Beds; Restraint Equipment.
6545	MAYBE	Replenishable Field Medical Sets, Kits, and Outfits
6550	NO	In Vitro Diagnostic Substances, Reagents, Test Kits and Sets
6605	YES	Navigational Instruments Includes Azimuths; Sextants; Octants; Compasses; Plotting Boards; Underwater Log Equipment; Air Position Indicators; Drift Meters.
6610	MAYBE	Flight Instruments Includes Air Speed Indicators; Rate of Climb Indicators; Bank and Turn Indicators; Pitot Tubes; Gyro Horizon Indicators;
6615	MAYBE	Automatic Pilot Mechanisms and Airborne Gyro Components Note Included in this class are gyro components of guided missiles. Excluded are complete gyro mechanisms and nonairborne gyro components, both of which are classified in the same classes as their next higher assemblies. Includes Automatic Pilot Regulators; Directional, Vertical, Bank and Turn, and Hydraulic Surface Gyro Controls; Airborne and Shipborne Automatic Pilot

		Mechanisms; Helicopter Automatic Stabilization Equipment.
6620	MAYBE	Engine Instruments Note- Instruments designed for use on both engines and other than engines are not included in this class and should be classified in the appropriate instruments class of Group 66. Includes All Engine Instruments, including Aircraft, Marine, and Vehicular; Fuel Pressure Gages; Manifold Pressure Gages; Oil Pressure Gages; Fuel Mixture Indicators; Engine Oil and Fuel Warning Devices.
6625	MAYBE	Electrical and Electronic Properties Measuring and Testing Instruments, Includes Test Leads and Test Lead Attachments; Test instruments designed for communication equipment; Test instruments designed for use with electronic equipment classified in two or more FSC groups.
6635	MAYBE	Physical Properties Testing and Inspection Includes Destructive and Nondestructive Inspection Equipment such as Fluorescent Penetrant Inspection Units; Magnetic Inspection Units; Industrial X-Ray Machines; Industrial X-Ray Film; Tensiometers; Material Hardness Testers.
6640	MAYBE	Laboratory Equipment and Supplies Includes Laboratory Glassware; Laboratory Funnels; Laboratory Furnaces; Glass Beads; Laboratory White Sand; Litmus Paper; Paper Filters; Insect Transfixion Pins; Laboratory Glass Wool; Laboratory Furniture, except Dental Laboratory
6645	MAYBE	Time Measuring Instruments Includes Clocks; Job Recording Devices; Time Recorders; Time

		Stamps, Watch and Clock Movements; Watches.
6650	MAYBE	Optical Instruments, Test Equipment, Components and Accessories Includes Binoculars; Magnifiers; Microscopes; Periscopes; Telescopes; Optical Elements, such as Lens, Prisms, Windows; Optical Benches and Associated Devices; Endoscopes, Fiber Optics (Non- Medical).
6660	MAYBE	Includes Meteorological Balloons; Radiosonde Sets; Radarsonde Sets. 6665 Hazard-Detecting Instruments
6665	MAYBE	Includes Radiac Equipment; Gas Detecting Equipment; Land Mine Detecting Equipment.
6670	MAYBE	Industrial, Postal, and Laboratory Scales and Balances. 6675 Drafting, Surveying
6675	MAYBE	Includes Drawing Instruments, Drafting Tools; Engineering and Architectural Scales; Levels; Transits; Photogrammetric Instruments; Astrolabes; Level Rods; Plane Tables; Surveying Altimeters; Theodolites.
6680	MAYBE	Liquid and Gas Flow, Liquid Level, and Mechanical Motion Measuring Instruments Includes Liquid Level Float Instruments; Revolution Counters; Speedometers; Rotation Measuring Instruments and Apparatus; Oxygen Flow Indicators; Tachometers, including Engine Tachometers.
6685	MAYBE	Pressure, Temperature, and Humidity Measuring and Controlling Instruments Includes Thermometers, including Engine Thermometers; Pressure Gages; Thermocouple Leads; Resistance Bulbs.
6695	MAYBE	Combination and Miscellaneous Instruments Includes Flow-Pressure

		Instruments; Taximeters; Dynamometers.
6810	NO	Chemicals and Chemical Products
6830	NO	Chemicals and Chemical Products
6840	NO	Chemicals and Chemical Products
6850	NO	Chemicals and Chemical Products
7025	MAYBE	ADP Input/Output and Storage Devices Note This class includes devices used to control and transfer information to and from a Computer (as modified).The input device is used for transferring data and instructions into a computer. The output device is used to transfer results of processing by the computer to ADP peripheral devices. Input/output devices combine the above functions in the same device. This class includes printers, display units, disk drive units (magnetic, optical and floptical), tape drive units, terminals, data entry devices and transfer units. Also includes Optical Compact Disk (CD) devices used for the storage and retrieval of data and firmware.
7045	MAYBE	ADP Supplies Note This class includes ADP tape seal bands, reels and hubs, carrying cases, canisters, and the like. Also includes all nonrecorded magnetic recording media designed to be used with ADP equipment, such as magnetic tape, removable disk packs, magnetic cards, cassettes, and diskettes. Also includes Optical Disks used for the storage of data.
7050	MAYBE	ADP Components Note-This class includes ADP Component Assemblies that are parts of analog, digital or hybrid data processing devices. Excluded from the class are items for which more specific classifications are suitable. The FSC structure and indexes will govern

		the classification of those items permitted classification in a single class only.
7210	NO	Household and Commercial Furnishings and Appliances
7290	NO	Household and Commercial Furnishings and Appliances
7310	MAYBE	Food Cooking, Baking, and Serving Equipment Note-This class includes warming and/or chilling equipment used for the display and serving of food. Includes Warming and/or Chilling Tables, Stationary and Portable; Serving Carts; Field and Mobile Baking Ovens; Toasters; Waffle Irons; Grills; Special Aircraft, Marine, and Railway Type Food Cooking
7510	NO	Office Supplies and Devices
7530	NO	Office Supplies and Devices
7690	NO	Books, Maps, and Other Publications
8010	NO	Brushes, Paints, Sealers, and Adhesives
8020	NO	Brushes, Paints, Sealers, and Adhesives
8030	NO	Brushes, Paints, Sealers, and Adhesives
8040	NO	Brushes, Paints, Sealers, and Adhesives
8110	YES	Drums and Cans Includes Barrels; Kegs; Shipping and Storage Pails; Collapsible Tubes; Mailing and Filing Tubes; Closures for Drums and Cans.
8115	YES	Boxes, Cartons, and Crates Includes Shoe Boxes; Beer Cases; Pill Boxes; Piano Cases; Engine Boxes; Bombsight Boxes.
8120	YES	Commercial and Industrial Gas Cylinders Note-This class includes empty commercial and industrial gas cylinders and their caps, valves, and valve spare parts.
8125	YES	Bottles and Jars Includes Shipping Jugs and Carboys; Ampoules.

8145	YES	Specialized Shipping and Storage Containers Note-This class includes only reusable and repairable containers specially designed for shipping and storage of specialized equipment, i.e., shipping and storage containers for components of aircraft, space vehicles, automotive vehicles, ships, ground communication equipment, etc. Includes Specially designed components (not elsewhere classifiable) peculiar to special shipping and storage containers as delimited under this class.
8305	NO	Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags
8310	NO	Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags
8315	NO	Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags
8340	NO	Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags
8345	NO	Textiles, Leather, Furs, Apparel and Shoe Findings, Tents and Flags
8405	NO	Clothing, Individual Equipment, and
8415	NO	Clothing, Individual Equipment, and
8430	NO	Clothing, Individual Equipment, and
8460	NO	Clothing, Individual Equipment, and
8465	NO	Clothing, Individual Equipment, and
8475	NO	Clothing, Individual Equipment, and
8950	NO	Subsistence, food
8960	NO	Subsistence, food
9150	NO	Fuels, Lubricants, Oils, and Waxes
9160	NO	Fuels, Lubricants, Oils, and Waxes
9320	YES	Rubber Fabricated Materials Includes Natural and Synthetic Rubber Fabricated Materials, such as Rubber Sheets, Structural Rubber Shapes, Strips.
9330	YES	Plastics Fabricated Materials Includes Cellulose Acetate and other plastics, Bars, Rods, Sheets, and Strips.
9340	NO	Glass Fabricated Materials Includes Glass Rods, Bars, and Tubing;

		Optical Glass Blanks; Structural and Building Glass; Glass Blocks.
9390	NO	Miscellaneous Fabricated Nonmetallic Materials Includes Cork Fabricated Basic Materials; Asbestos Fabricated Materials; Manufactured Mica; Minerals for scientific and technical use (cut but not mounted); Pottery Supplies; Catgut and Wormgut;
9505	NO	Metal Bars, Sheets, and Shapes, bulk
9510	NO	Metal Bars, Sheets, and Shapes, bulk
9515	NO	Metal Bars, Sheets, and Shapes, bulk
9520	NO	Metal Bars, Sheets, and Shapes, bulk
9525	NO	Metal Bars, Sheets, and Shapes, bulk
9530	NO	Metal Bars, Sheets, and Shapes, bulk
9535	NO	Metal Bars, Sheets, and Shapes, bulk
9540	NO	Metal Bars, Sheets, and Shapes, bulk
9905	YES	Signs, Advertising Displays, and Identification Plates Includes Electric Signs; Sign Boards; Display Stands; Mannequins and other display forms; Printed Signs; General Purpose Identification Tags and Blanks, Nonpersonal; Plates and Tags for specific applications.
9999	MAYBE	Miscellaneous Items Includes only those items which cannot conceivably be classified in any existing classes

APPENDIX E. UNIT OF ISSUE DESCRIPTIONS

Unit of issue abbreviations and table format adapted from the NAVSUP P-485 Afloat Supply Operations Manual (Naval Supply Systems Command 2015).

Unit of Issue	Description	Unit of Issue	Description
AM	AMPOULE	LB	POUND
AT	ASSORTMENT	LG	LENGTH
AY	ASSEMBLY	LI	LITER
BA	BALL	LT	LOT
BD	BUNDLE	MC	THOUSAND CUBIC FEET
BE	BALE	ME	MEAL
BF	BOARD FOOT	MM	MILLIMETER
BG	BAG	MR	METER
BK	BOOK	MX	THOUSAND (1000)
BL	BARREL	OT	OUTFIT
BO	BOLT	OZ	OUNCE
BR	BAR	PD	PAD
BT	BOTTLE	PG	PACKAGE
BX	BOX	PK	PACKAGE BUY
CA	CARTRIDGE	PM	PLATE
CB	CARBOY	PR	PAIR
CD	CUBIC YARD	PT	PINT
CE	CONE	PZ	PACKET
CF	CUBIC FOOT	QT	QUART
CK	CAKE	RA	RATION
CL	COIL	RL	REEL
CM	CENTIMETER	RM	REAM (500 SHEETS)
CN	CAN	RO	ROLL
CO	CONTAINER	SD	SKID
CS	CASE	SE	SET
CT	CARTON	SF	SQUARE FOOT
CU	CUBE	SH	SHEET
CY	CYLINDER	SK	SKIEN

Unit of Issue	Description	Unit of Issue	Description
CZ	CUBIC METER	SL	SPOOL
DR	DRUM	SO	SHOT
DZ	DOZEN	SP	STRIP
EA	EACH	SV	SERVICE
EN	ENVELOPE	SX	STICK
FT	FOOT	SY	SQUARE YARD
FV	FIVE	TD	TWENTY-FOUR
FY	FIFTY	TE	TEN
GL	GALLON	TF	TWENTY-FIVE
GP	GROUP	TN	TON
GR	GROSS	TO	TROY OUNCE
HD	HUNDRED (100)	TS	THIRTY-SIX
HK	HANK	TU	TUBE
IN	INCH	VI	VIAL
JR	JAR	XX	DOLLARS FOR SERVICES
KG	KILOGRAM	YD	YARD
KT	KIT		

APPENDIX F. LIST OF USN LEVEL 1–3 COMMERCIAL AM ASSETS

Table 29. Listing of USN Level 1-3 Commercial AM Assets. Adapted from: NAVAIR Navy Price Fighter AM Group (2022)

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	Mid-Atlantic Regional Maintenance Center (MARMC)	Depot/Shipyard/FRC	Stratasys	Dimension sst1200es	Material Extrusion	Industrial	10 x 10 x 12	ABSplus	3–Capital
NAVAIR	NAWC Lakehurst	WC/SC/Lab	Stratasys	250mc	Material Extrusion	Industrial	10 x 10 x 12		2–Northeast
NAVAIR	NAWC Lakehurst	WC/SC/Lab	Stratasys	Dimension SST 1200BST	Material extrusion	Industrial	10 x 10 x 12	ABSplus	2–Northeast
NAVAIR	NAWC Lakehurst	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Nylon with capability to reinforce with layers of carbon fiber, Kevlar, or fiberglass	2–Northeast
NAVAIR	NAWC Lakehurst	WC/SC/Lab	Stratasys	Objet Eden 350V	Material jetting	Industrial	13.4 x 13.4 x 7.9	Tango, Vero Plastics	2–Northeast
NAVAIR	NAWC Patuxent River	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	3–Capital
NAVAIR	NAWC St. Inigoes	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16		3–Capital
NAVAIR	NAWC St. Inigoes	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16		3–Capital
NAVAIR	NAWC St. Inigoes	WC/SC/Lab	Stratasys	Objet 260 Connex 3	Material jetting	Industrial	10 x 10 x 8		3–Capital
NAVAIR	NAWC St. Inigoes	WC/SC/Lab	Raise3D	Raise3D N2 Plus	Material extrusion	Industrial	12 x 12 x 24		3–Capital
NAVAIR	NAWC St. Inigoes	WC/SC/Lab	Stratasys	Stratasys F370	Material extrusion	Industrial	14 x 10 x 14		3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVAIR	FRC East	Depot/Shipyard/FRC	Stratasys	Dimension SST 1200es	Material extrusion	Industrial	12 x 12 x 12	ABSplus	4–Southeast
NAVAIR	FRC East	Depot/Shipyard/FRC	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	4–Southeast
NAVAIR	FRC East	Depot/Shipyard/FRC	Raise3D	Raise3D N2 Plus	Material extrusion	Industrial	12 x 12 x 24	PLA, ABS, PETG, PC, Tough PLA, Reinforced Nylon, TPU	4–Southeast
NAVAIR	FRC East	Depot/Shipyard/FRC	Markforged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Onyx, Nylon, Continuous Fiber Reinforcement (Carbon, Kevlar, HSHT Fiberglass, Standard Fiberglass)	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Formlabs	Form 3	Vat Polymerization	Industrial	5.7 x 5.75 x 7.3	Modeling resins, tough resin, high temp resin, durable resin	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	14 x 12 x 14	ULTEM 9085	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	ABS	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	HP	MJF 4200	Powder bed fusion	Industrial	15 x 11.2 x 15	PA 12 (Nylon 12)	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	HP	MJF 4200	Powder bed fusion	Industrial	15 x 11.2 x 15	PA 12 (Nylon 12)	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Strataysy/Z-Corp	Spectrum Z510	Binder jetting	Industrial	10 x 14 x 8	Zp150 powder material, Zb60 binder	4–Southeast
NAVAIR	FRC Southeast	Depot/Shipyard/FRC	Stratasys	uPrint SE	Material extrusion	Industrial	6 x 8 x 6	ABS only	4–Southeast
NAVAIR	NAWCTSD	WC/SC/Lab	Stratasys	Connex2 Objet500	Material jetting	Industrial	19 x 15 x 8	Various Photopolymer Prototyping Plastics (Vero, Digital ABS, Tango)	4–Southeast
NAVAIR	NAWCTSD	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, Nylon 12CF, ULTEM-9085, ULTEM-1010	4–Southeast
USMC	1st Maintenance Batallion	Field/Home Station	Big Metal Additive	DMS	Directed Energy Deposition	Industrial			9–West

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	NUWC, Keyport	WC/SC/Lab	3D Systems	3DSystems/ Vanguard si2 2500	Powder bed fusion	Industrial	12.5 x 13.5 x 15 (XYZ)	PA 11 Black	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	3NTR	A2V4 Plural	Material extrusion	Industrial	24 x 16 x 20	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Dimension 1200	Material extrusion	Industrial	10 x 10 x 12	ABSPlus	9–West
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Dimension 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSPlus	9–West
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Dimension 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSPlus	9–West
NAVFAC	EXWC–Dry Lab	WC/SC/Lab	Stratasys	Dimension SST 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSplus	9–West
NAVSEA	NSWC, Corona	WC/SC/Lab	Stratasys	Dimension SST 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSplus	9–West
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Fortus 250mc	Material extrusion	Industrial	10 x 10 x 12	ABS M30, PC ABS, PC10, PC, Nylon-12	9–West
USMC	1st Maintenance Batallion	EXMAN	Stratasys	Fortus 250mc	Material extrusion	Industrial	10 x 10 x 12	ABS M30, PC ABS, PC10, PC, Nylon-12	9–West
NAVAIR	FRC Southwest	Depot/Shipyard/FRC	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	9–West
USMC	3rd Maint Bn	Field	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	International
USMC	3rd Maint Bn	Field	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	International
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Connex3 Objet260	Material extrusion	Industrial	10 x 9.9 x 7.9		9–West
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Dimension SST 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSplus	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Dimension SST 1200es	Material extrusion	Industrial	10 x 10 x 12	ABSplus	10–Northwest

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Connex3 Objet260	Material extrusion	Industrial	10 x 9.9 x 7.9		9–West
NAVSEA	NSWC, Corona Updated- Fallbrook Detachment	WC/SC/Lab	LulzBot	Pro	Material extrusion	Industrial	11 x 11 x 11.2	PLA, ABS, PETG, Alloy 910, nylon, bronzeFill, CopperFill, Stainless Steel PLA	9–West
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Dimension SST 768	Material extrusion	Industrial	8x8x12	ABSplus	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Dimension SST 768	Material extrusion	Industrial	8x8x12	ABSplus	10–Northwest
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2	Material extrusion	Industrial	12 x 12 x 11.8	PLA, ABS, HIPS, PC, TPU, TPE, Nylon, PETG, ASA, PP, PVA , Glass Fiber Infused, Carbon Fiber Infused, Metal Fill, Wood Fill	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2	Material extrusion	Industrial	12 x 12 x 11.8	PLA, ABS, HIPS, PC, TPU, TPE, Nylon, PETG, ASA, PP, PVA , Glass Fiber Infused, Carbon Fiber Infused, Metal Fill, Wood Fill	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2	Material extrusion	Industrial	12 x 12 x 11.8	PLA, ABS, HIPS, PC, TPU, TPE, Nylon, PETG, ASA, PP, PVA , Glass Fiber Infused, Carbon Fiber Infused, Metal Fill, Wood Fill	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2	Material extrusion	Industrial	12 x 12 x 11.8	PLA, ABS, HIPS, PC, TPU, TPE, Nylon, PETG, ASA, PP, PVA , Glass Fiber Infused, Carbon Fiber Infused, Metal Fill, Wood Fill	9–West
NAVSEA	Portsmouth Naval Shipyard (PNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	14 x 10 x 10	ABS M30, PC ABS, PC10, PC, Nylon-12, ULTEM 9085	1–New England
NAVSEA	Portsmouth Naval Shipyard (PNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	14 x 10 x 10	ABS M30, PC, ULTEM 1010	1–New England
NAVSEA	Portsmouth Naval Shipyard (PNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, Nylon	1–New England
NAVSEA	Portsmouth Naval Shipyard (PNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, PC ABS, PC-ISO, Nylon-12, Ultem 9085	1–New England

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	Portsmouth Naval Shipyard (PNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	TBD	1–New England
NAVSEA	NUWC, Newport	WC/SC/Lab	Stratasys	Fortus 250mc	Material extrusion	Industrial	10 x 10 x 12	ABS-M30	1–New England
NAVSEA	NUWC, Newport	WC/SC/Lab	Stratasys	Objet 30 Prime	Material Jetting	Industrial	5.5 x 7.5 x 11.5	Tango, Vero	1–New England
NAVSEA	NUWC, Newport	WC/SC/Lab	Raise3D	Pro 2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA, ABS, HIPS, PC, TPU, TPE, Nylon, PETG, ASA, PP, PVA,	1–New England
NAVSEA	NUWC, Newport		3D Systems	ProX800	Vat polymerization	Industrial	25.6 x 29.5 x 21.65	Clear View, Accura Materials	1–New England
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA, nGen	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA, nGen	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA, nGen	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Raise3D	Pro2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA, nGen	9–West
USMC	Task Force Al Asad	Field	Stratasys	Fortus 250mc	Material extrusion	Industrial	10 x 10 x 12	ABS M30, PC ABS, PC10, PC, Nylon-12	International
NAVWA R	NIWC Pacific, San Diego	WC/SC/Lab	AXIOM	AIRWOLF	Material extrusion	Industrial	12 x 8 x 9.5	PLA, ABS, PETG, nGen, INOVA-1800, HIPS, t-glase, Alloy 910, Polyamide, Nylon 645, PC	9–West
NAVFAC	EXWC–Expeditionary Maintenance Center 1 (EMC 1)	Depot/Shipyard/FRC	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	9–West
NAVFAC	EXWC–EXWC / NCG 1 Fab Lab (Bldg. 1250)	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	9–West
NAVFAC	EXWC–NCG 1 TACFAB Kit for NMCB 1/11/133	Field	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	9–West
NAVFAC	EXWC–NCG 1 TACFAB Kit for NMCB 1/11/133	Field	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	9–West
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	14 x 10 x 10	ABS M30, PC ABS, PC10, PC, Nylon-12	10–Northwest

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	14 x 10 x 10	ABS M30, PC ABS, PC10, PC, Nylon-12	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	10–Northwest
NAVSEA	NSWC, Corona Updated-Fallbrook Detachment	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Plastics: Onyx, Tough Nylon Fiber: Carbon Fiber, Fiberglass, Kevlar, High Strength/High Temp Fiberglass	9–West
NAVSEA	NSWC, Carderock	WC/SC/Lab	Cosine	AM-1	Material extrusion	Industrial	42 x 33 x 33	CF-ABS, ABS	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABS, ASA, TPU	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, ABS-ESD7, ABS-M30, ASA, Nylon 12, Ultem 9085	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, ABS-ESD7, ABS-M30, ASA, Nylon 12, Ultem 9085	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	NSWC, Carderock	WC/SC/Lab	3D Systems	iPro 9000 XL	Vat polymerization	Industrial	59 x 30 x 22	Accura 60	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Nylon, Continous Fiber	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MakerBot	Method X	Material extrusion	Industrial	7.5 x 7.5 x 7.75	PETG, PLA, ABS, ASA, PVA	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	Objet350 Connex3	Material Jetting	Industrial	13.4x13.4x7.9	Tango, RGD 515, RGD 531, RGD 851, RGD 836, FullCure 810, FullCure 835, FullCure 850, FullCure 980, FullCure 515, Full Cure 535, FLX 935, FLX 985	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	Objet500 Connex3	Material Jetting	Industrial	19.3 x 15.4 x 7.9	Tango, RGD 515, RGD 531, RGD 851, RGD 836, FullCure 810, FullCure 835, FullCure 850, FullCure 980, FullCure 515, Full Cure 535, FLX 935, FLX 986	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Onyx	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	UnionTech	RSPro 600	Vat polymerization	Industrial	23.6 x 23.6 x 19.7	Somos EvolVe 128	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	3D Systems	SLA 5000	Vat polymerization	Industrial	21.6 x 15.5 x 11.8	Somos EvolVe 128	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	uPrint SE	Material extrusion	Industrial	6 x 8 x 6	ABS	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABS	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABS	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Onyx, Continuous Fiber	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Onyx, Continuous Fiber	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Dimension Elite	Material extrusion	Industrial	8 x 8 x 12	ABS	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Nano Dimension	Dragonfly Pro	Other	Industrial	7.9 x 7.9 x .12	3d printed electronics (PCB-like)	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD7, ABS-M30, ASA, Nylon 12, Polycarbonate,	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
								Ultem 9085, Ultem 1010, ST-130	
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, NYLON-12, ASA, ULTEM 1011	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Fortus F370	Material extrusion	Industrial	14 x 10 x 10	ABS, TPU	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Objet Connex3 Objet260	Material Jetting	Industrial	10.0 x 9.9 x 7.9 in	Vero, Digital ABS Plastics, Agilus30	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Objet Eden 500V	Material Jetting	Industrial	19.3 x 15.4 x 7.9	UV cured Tango, Vero Plastics	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Stratasys	Objet500 Connex	Material Jetting	Industrial	19.3 x 15.4 x 7.9	UV cured Tango, Vero, Digital ABS Plastics	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Custom Fabrication	Custom Fabrication	Material extrusion	Industrial		Energetic Materials	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Dimension Elite	Material extrusion	Industrial	8 x 8 x 12	ABSplus	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ASA, ABS, PLA	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Formlabs	Form 3	Vat Polymerization	Industrial	5.7 x 5.75 x 7.3	Photopolymer resin	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	14x10x10	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, ULTEM 9085, Nylon 12	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
	Technology Division								
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	14x10x10	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, ULTEM 9085, Nylon 12	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, ULTEM 9085, ULTEM 1010, Nylon 12, Nylon 12CF	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, Nylon 12	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD, ABSi, ABS-M30, ABS-M30i, ASA, PC, PC-ABS, PC-ISO, ULTEM 9085, ULTEM 1010, Nylon 12, Nylon 12CF, ST130	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, ULTEM 9085, Nylon 12	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	3NTR	A2	Material extrusion	Industrial	23.6 x 12.7 x 19.6	PLA, ABS, Nylon, PC, PEKK	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Nylon-CF Composites, Continuous CF, Glass, Kevlar, Nylon	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	Stratasys	Objet350 Connex3	Material Jetting	Industrial	13 x 13 x 8	UV Cured Tango+, Vero, Digital ABS	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	Origin	One	Vat polymerization	Industrial	7.5 x 4.25 x 13.7	Photopolymer Resins, Silicon	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABS	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Nylon-CF Composites, Continuous CF, Glass, Kevlar, Nylon	3–Capital
NAVSEA	Norfolk Naval Shipyard (NNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 250mc	Material extrusion	Industrial	10 x 10 x 12	ABSplus	3–Capital
NAVSEA	Norfolk Naval Shipyard (NNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16	ABS-M30, PC-ABS, Nylon 12, ULTEM-9085	3–Capital
NAVSEA	Norfolk Naval Shipyard (NNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, ABS-ESD7, ABS-M30, ASA, Nylon 12, Ultem 9085	3–Capital
NAVSEA	Norfolk Naval Shipyard (NNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	PC, ABS-ESD7, ABS-M30, ASA, Nylon 12, Ultem 9085	3–Capital
NAVSEA	NAVSEA04	Field	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 10	ABS-M30, PC-ABS, Diran, ASA, TPU,	3–Capital
NAVSEA	NAVSEA04	Field	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD7, ABS-M30, ABS-M30i, ASA, PC-ABS, PC-ISO, PC, Nylon 12CF, Nylon 12, ULTEM-9085, Ultem 1010, ST130, Antero	3–Capital
NAVSEA	NAVSEA04	Field	Stratasys	Fortus 900mc	Material extrusion	Industrial	24 x 36 x 36	ABS-ESD7, ABS-M30, ABS-M30i, ASA, PC-ABS, PC-ISO, PC, Nylon 6, Nylon 12, ULTEM-9085, Ultem 1010, PPSF PPSU, ST130	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD7, ABS-M30, Polycarbonate, Ultem 9085	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Nylon-6 with carbon fiber, Kevlar, or fiberglass reinforcement	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	Stratasys	Objet500 Connex	Material Jetting	Industrial	19.3 x 15.4 x 7.9	Tango, Vero, Digital ABS Plastics	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Nylon-6 with carbon fiber	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	Raise3D	Pro 2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	ABS, Nylon with Carbon Fiber,PLA,PVA	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	Raise3D	Pro 2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	ABS, Nylon with Carbon Fiber,PLA,PVA	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	Raise3D	Pro2	Material extrusion	Industrial	12 x 12 x 11.8	ABS, Nylon with Carbon Fiber,PLA,PVA	3–Capital
NAVSEA	NSWC, Dahlgren (Dam Neck)	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Nylon-6 with carbon fiber, Kevlar, or fiberglass reinforcement	3–Capital
NAVSEA	NSWC, Panama City	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Carbon Fiber, Fiberglass, Kevlar, HSHT Fiberglass, Onyx	4–Southeast
NAVSEA	NSWC, Panama City	WC/SC/Lab	3D Systems	ProJet 3510 HDPlus	Material jetting	Industrial	11.8 x 7.3 x 7.9	VisiJet Crystal	4–Southeast
NAVSEA	NSWC, Panama City	WC/SC/Lab	3D Systems	Projet 860	Binder jetting	Industrial	20 x15 x 9	VisiJet PXL (gypsum)	4–Southeast
NAVSEA	NSWC, Panama City	WC/SC/Lab	3D Systems	SLA 3500	Vat polymerization	Industrial	14 x 14 x 15	Somos Watershed XC 11122	4–Southeast
NAVSEA	NSWC, Panama City	WC/SC/Lab	3D Platform	Workbench Pro 300	Material extrusion	Industrial	39 x 39 x 27	ABS, PLA, PETG, PC	4–Southeast
NAVSEA	NSWC Crane	WC/SC/Lab	Optomec	AJ5X	Other	Industrial	7.9 x 11. x 7.9	Organic Inks	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Nano Dimension	Dragonfly Pro	Other	Industrial	7.9 x 7.9 x .12	Dielectric Nanoparticle Photopolymer & AgCite Conductive Inks	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABS, ASA, PLA, TPU	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABS, ASA, PLA, TPU	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14	ABS, ASA	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	F900	Material extrusion	Industrial	36 x 24 x 36	ASA, ABS-ESD7, PC, Nylon 12, Nylon 12CF, ULTEM 9085,	5–Midwest

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
								ULTEM 1010, ST-130, Antero 800NA, Antero 840CN03	
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	Fortus 360mc	Material extrusion	Industrial	16 x 14 x 16	ABS-M30, PC	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-M30, ABS-ESD7, ASA, PCA-ABS, PC, Nylon 12, ULTEM 9085, ULTEM 1010	5–Midwest
NAVSEA	NSWC Crane	WC/SC/Lab	Stratasys	Objet1000 Plus	Material Jetting	Industrial	39.3 x 31.4 x 19.6	Vero (ABS-Like), Tango (Rubber-like)	5–Midwest
NAVFAC	EXWC–Expeditionary Maintenance Center 1 (EMC 1)	Depot/Shipyard/FRC	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Nylon-6 with carbon fiber, Kevlar, or fiberglass reinforcement	9–West
NAVSEA	NSWC, Port Hueneme	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Nylon-6 with carbon fiber, Kevlar, or fiberglass reinforcement	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Plastics: Onyx, Tough Nylon Fiber: Carbon Fiber, Fiberglass, Kevlar, High Strength/High Temp Fiberglass	9–West
NAVSEA	Pearl Harbor Naval Shipyard (PHNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 360mc	Material extrusion	Industrial	14 x 10 x 10	ABS M30, PC ABS, PC10, PC, Nylon-12	9–West
NAVSEA	NSWC, Port Hueneme	WC/SC/Lab	Stratasys	Fortus 360mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, PC10, PC, Nylon-12	9–West
NAVSEA	NUWC, Keyport	WC/SC/Lab	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	ASA, ABS-ESD7, PC-ABS, ULTEM9085, ULTEM1010	10–Northwest
NAVAIR	FRC Southwest	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	9–West
NAVSEA	Pearl Harbor Naval Shipyard (PHNSY)	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS M30, PC ABS, PC10, PC, Nylon-12, ULTEM	9–West
NAVSEA	NUWC, Keyport	WC/SC/Lab	HP	Jet Fusion 3D 4200	Powder bed fusion	Industrial	15 x 11.2 x 15 (XYZ)	Nylon 12	10–Northwest
NAVSEA	NSWC, Port Hueneme	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ABS-ESD, ABSi, ABS-M30, ABS-M30i, PC, PC-ABS, PC-ISO, PPSF, ULTEM 9085, Nylon 12	9–West

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ULTEM, NYLON12CF, ABS, PLA, POLYCARBONATE, ANTERO, ASA	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ULTEM, NYLON12CF, ABS, PLA, POLYCARBONATE, ANTERO, ASA	9–West
NAVWAR	NIWC Atlantic, Norfolk	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Onyx	3–Capital
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	BigRep	BigRep ONE	Material extrusion	Industrial	39 x 39 x 39	PLA, ABS, Nylon, Ninja Flex,T-Glase, PVA, HIPS	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	Stratasys	F270	Material extrusion	Industrial	10 x 12 x 10	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	Stratasys	Fortus 380mc	Material extrusion	Industrial	16 x 14 x 16	Nylon 12	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	AON	M2	Material extrusion	Industrial	18 x 18 x 25	ABS, PC/PBT, PEEK, Ultem	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Onyx with continuous fiber reinforcement using Fiberglass, Kevlar, Carbon Fiber, HSHT Fiberglass	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Mark Two	Material extrusion	Industrial	12.6 x 5.2 x 6	Onyx with continuous fiber reinforcement using Fiberglass, Kevlar, Carbon Fiber, HSHT Fiberglass	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Onyx	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Onyx	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Onyx One	Material extrusion	Industrial	12.5 x 5 x 6	Onyx	4–Southeast

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	Raise3D	Pro 2 Plus	Material extrusion	Industrial	12 x 12 x 23.8	PLA	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Onyx with continuous fiber reinforcement using Fiberglass, Kevlar, Carbon Fiber, HSHT Fiberglass	4–Southeast
NAVWAR	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	X7	Material extrusion	Industrial	13 x 10.6 x 7.9	Onyx with continuous fiber reinforcement using Fiberglass, Kevlar, Carbon Fiber, HSHT Fiberglass	4–Southeast
NAVWAR	NIWC Atlantic, Tampa	WC/SC/Lab	Stratasys	Fortus 380mc	Material extrusion	Industrial	16 x 14 x 16	ABS, ASA, PC10	4–Southeast
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ULTEM, NYLON12CF, ABS, PLA, POLYCARBONATE, ANTERO, ASA	9–West
USMC	1st Maintenance Batallion	EXMAN	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16	ULTEM, NYLON12CF, ABS, PLA, POLYCARBONATE, ANTERO, ASA	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	J750	Material extrusion	Industrial	19.3 x 15.4 x 7.9	https://www.stratasys.com/3d-printers/j735-j750	9–West
NAVAIR	FRC Southwest	Depot/Shipyard/FRC	Stratasys	Fortus 900mc	Material extrusion	Industrial	36 x 24 x 36	ABSi, ABS-ESD7, ABS-M30, ABS-M30i, PC-ABS, PC-ISO, PC, Nylon 12, ULTEM-9085, PPSF PPSU	9–West
USMC	MALS-39	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		9–West
USMC	MALS-24	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		9–West
USMC	MALS-11	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		9–West
USMC	MALS-16	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		9–West

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
USMC	MALS-13	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		9–West
USMC	MALS-12	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		International
NAVSEA	NUWC, Keyport	WC/SC/Lab	Custom Fabrication	Mobile Robotic Direct Metal Deposition (MRDMD) System	Directed Energy Deposition	Industrial	44 x 44 x 44 (approx)	Metal powders	10–Northwest
USMC	MALS-36	Hangar / Mobile Facility	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		International
NAVSEA	USS ESSEX	Field	Stratasys	uPrint SE	Material extrusion	Industrial	6 x 8 x 6	ABSplus	9–West
NAVSEA	NSWC, Corona Updated-Fallbrook Detachment	WC/SC/Lab	MakerBot	Method X	Material extrusion	Industrial	7.5 x 7.5 x 7.75	ABS, ASA, nylon, PETG, PLA, PVA,	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Cincinnati	SAAM HT	Material extrusion	Industrial	7.9 x 7.4 x 9.4	ULTEM, NYLON12CF	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Dimension Elite	Material extrusion	Industrial	8 x 8 x 12	ABS	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	Dimension Elite	Material extrusion	Industrial	8 x 8 x 12	ABS	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABSPlus	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABSPlus	9–West
USMC	CLB-31	HQ Bld	Stratasys	uPrint SE Plus	Material extrusion	Industrial	8 x 8 x 6	ABSPlus	International

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Zmorph	VX	Material extrusion	Industrial	9.2 x 9.8 x 6.5	TPE, PC/ABS, PET-G, PVA, PLA, ABS, Nylon	9–West
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	3D Systems	ProJet SD 3000	Material jetting	Industrial	11.8 x 7.3 x 8	VisiJet (Plastics)	10–Northwest
Other	Walter Reed Armed Forces National Medical Center	WC/SC/Lab	MCOR	Iris	Sheet Lamination	Industrial	10 x 6.6 x 5.9	Paper/Glue	3–Capital
Other	Walter Reed Armed Forces National Medical Center	WC/SC/Lab	Stratasys	Objet30	Material Jetting	Industrial	11.57 x 7.55 x 5.85	Vero Plastics	3–Capital
Other	Walter Reed Armed Forces National Medical Center	WC/SC/Lab	Stratasys	uPrint SE	Material extrusion	Industrial	6 x 8 x 6	ABSplus	3–Capital
Other	Walter Reed Armed Forces National Medical Center	WC/SC/Lab	Strataysy/Z-Corp	Zprinter 450	Binder jetting	Industrial	8 x 8 x 10	Gypsum type powder	3–Capital
Other	Walter Reed Armed Forces National Medical Center	WC/SC/Lab	Strataysy/Z-Corp	Zprinter 650	Binder jetting	Industrial	10 x 15 x 8	Gypsum type powder	3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16		3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	NRL	Laser Direct Write	Directed Energy Deposition	Industrial			3–Capital
USMC	MARCORSYSCOM PM Marine Equipment Rifle Squad (MERS)-Gruntworks	WC/SC/Lab	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16		3–Capital
USMC	MARCORSYSCOM SIAT	WC/SC/Lab	HP	Jet Fusion 3D 4200	Powder bed fusion	Industrial	15 x 11.2 x 15		3–Capital
USMC	MARCORSYSCOM SIAT	WC/SC/Lab	Stratasys	uPrint	Material extrusion	Industrial	6 x 8 x 6		3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
USMC	Methods of Entry School		Stratasys	Dimension 1200	Material extrusion	Industrial	10 x 10 x 12		3–Capital
USMC	MARCORLOGCOM Maintenance Center Albany (USMC)	Depot/Shipyard/FRC	Stratasys	Fortus 400mc	Material extrusion	Industrial	16 x 14 x 16		4–Southeast
USMC	MARCORLOGCOM Maintenance Center Albany (USMC)	Depot/Shipyard/FRC	EOS	M400	Powder Bed	Industrial	15.8 x 15.8 x 15.8		4–Southeast
USMC	2d Maint Bn	Field	Big Metal Additive	DMS	Directed Energy Deposition	Industrial			4–Southeast
USMC	2d Maint Bn	Depot/Shipyard/FRC	Stratasys	Fortus 450mc	Material extrusion	Industrial	16 x 14 x 16		4–Southeast
USMC	CLB-22	Field	Stratasys	F370	Material extrusion	Industrial	10 x 14 x 14		4–Southeast
NAVSEA	Puget Sound Naval Shipyard (PSNSY)	Depot/Shipyard/FRC	3D Systems	ProJet SD 3000	Material jetting	Industrial	11.8 x 7.3 x 8	VisiJet (Plastics)	10–Northwest
NAVAIR	NAWC China Lake	WC/SC/Lab	Stratasys	Fortus	Material extrusion	Industrial		ABS	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Stratasys	Objet500 Connex	Material Jetting	Industrial	19.3 x 15.4 x 7.9	Tango, Vero, Digital ABS	9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	Optomec	AJ200	Material jetting	Industrial	8 x 8 x 2	Aerosol Jetting conductive Ink	9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Dragonfly	2020	Other	Industrial			9–West
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	Optomec	AF200	Other	Industrial		Commercial and custom nano-particle functional fluids	9–West
USMC	SPMAGTF-CR-CC	Field	MarkForged	X#	Material extrusion	Industrial			International
USMC	SPMAGTF-CR-CC	Field	MarkForged	X#	Material extrusion	Industrial			International
USMC	MARCORLOGCOM Maintenance Center Albany (USMC)	Depot/Shipyard/FRC	EOS	M400	Powder Bed	Industrial	15.8 x 15.8 x 15.8		9–West
NAVAIR	NAWC China Lake	WC/SC/Lab	EOS	M290	Powder bed fusion	Industrial	9.8 x 9.8 x 12.8	Ti-6Al-4V, 17–4PH, AlSi10Mg, IN718, Maragin Steel MS1	9–West

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVAIR	FRC Southwest	Depot/Shipyard/FRC	3D Systems	sPro 60 HD	Powder bed fusion	Industrial		DuraForm PA (nylon)	9–West
NAVSEA	NSWC, Corona Updated-Fallbrook Detachment	WC/SC/Lab	Formlabs	Form 3L	Vat Polymerization	Industrial	13.2 x 7.9 x 11.8	Photopolymer resin	9–West
NAVAIR	FRC Southwest	Depot/Shipyard/FRC	3D Systems	iPro 8000	Vat polymerization	Industrial	25.6 x 29.5 x 21.65	Accura 25	9–West
NAVSEA	NSWC, Corona Updated-Fallbrook Detachment	WC/SC/Lab	Formlabs	Form 3	Vat Polymerization	Industrial	5.7 x 5.75 x 7.3	Photopolymer resin	9–West
USMC	MALS-39	Weld Shop	Centerline	SST Cold Spray		Industrial			9–West
NAVAIR	NAWC Lakehurst	WC/SC/Lab	EOS	M290	Powder bed fusion	Metal	9.8 x 9.8 x 12.8	Metal Powder	2–Northeast
NAVSEA	NSWC, Carderock	WC/SC/Lab	Diversified Machine Systems	2Cubed 5-axis	Directed Energy Deposition	Metal	24 x 24 x 24	Print–Any welding electrode; Machining–Aluminums	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Wolf/ABB	IRB-Series	Directed Energy Deposition	Metal	Large	Wire Materials	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4 PH, Tool Steels, Inconel, Ti64	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Grid Logic	POM DMD IC106	Directed Energy Deposition	Metal	16 x 16 x 16	Any metallic or cermic powder that meets size distribution	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	3D Systems	ProX 200	Powder bed fusion	Metal	5.5 x 5.5 x 4	Titanium, Inconel, Stainless Steel	3–Capital
NAVSEA	NSWC, Carderock	WC/SC/Lab	Desktop Metal	Studio	Material extrusion	Metal	11.8 x 7.87 x 7.87	Metal Injection Molding Materials	3–Capital
NAVSEA	NAVSEA04	Field	EOS	M280	Powder bed fusion	Metal	10 x 10 x 11	Maraging Steel, Stainless Steel	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	EOS	M280	Powder bed fusion	Metal	9.85 x 9.85 x 12.8	18% Ni Maraging 300	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	EOS	M290	Powder bed fusion	Metal	9.8 x 9.8 x 12.8	Maraging	3–Capital
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Desktop Metal	Studio	Material extrusion	Metal	11.8 x 7.87 x 7.87	Metal Injection Molding Materials	3–Capital

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVSEA	NSWC, Dahlgren	WC/SC/Lab	Desktop Metal	Studio	Material extrusion	Metal	11.8 x 7.87 x 7.87	Metal Injection Molding Materials	3–Capital
NAVSEA	NSWC, Indian Head Explosive Ordnance Disposal Technology Division	WC/SC/Lab	ConceptLaser	M2	Powder bed fusion	Metal	10 x 10 x 11	Tool Steel, 17–4 SS, 316 SS, Inconel	3–Capital
NAVSEA	NSWC, Philadelphia	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4 SS, A2/D3/H13 Steel, Inconel 625, Copper	3–Capital
NAVSEA	NAVSEA04	Field	EOS	M290 Metal	Powder bed fusion	Metal	10 x 10 x 11	Maraging Steel, IN625, 316SST, 17–4ph SST, 15–5 SST, Titanium	3–Capital
NAVSEA	NSWC, Panama City	WC/SC/Lab	EOS	M290	Powder bed fusion	Metal	9.8 x 9.8 x 12.8	17-4 SS	4–Southeast
NAVSEA	NUWC, Keyport	WC/SC/Lab	EOS	M290	Powder bed fusion	Metal	9.8 x 9.8 x 12.8	316 SS, 17–4 SS, Inconel 625, AlSi10Mg Al, Ti 6Al-4V	10–Northwest
NAVWA R	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	Tool steel, stainless steel, ceramic support material	4–Southeast
NAVWA R	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	Tool steel, stainless steel, ceramic support material	4–Southeast
NAVWA R	NIWC Atlantic, Charleston	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	Tool steel, stainless steel, ceramic support material	4–Southeast
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	ExOne	Innovent+	Material jetting	Metal	6.3 x 2.5 x 2.5		3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	ConceptLaser	M2 Multilaser	Powder bed fusion	Metal	10 x 10 x 11		3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	ExOne	M-Flex	Material jetting	Metal	15.75 x 9.84 x 9.84		3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	Hurco	VMX-42Ui	Hybrid	Metal	42 x 24 x 20.4		3–Capital
Other	Naval Research Laboratory (NRL)	WC/SC/Lab	Accutex	WIRE EDM	Directed Energy Deposition	Metal			3–Capital
USMC	2d Maint Bn	Field	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9		4–Southeast
NAVSEA	NSWC, Port Hueneme	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4 Stainless Steel	9–West

	Site	Facility	Company	Model	Process Type	Classification	Build Volume (in)	Primary Materials Processed	Region
NAVWAR	NIWC Pacific, San Diego	WC/SC/Lab	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4PH Stainless, H13 Tool Steel	9–West
USMC	1st Maintenance Batallion	Field/Home Station	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4PH Stainless, H13 Tool Steel	9–West
USMC	1st Maintenance Batallion	EXMAN	3D Hybrid	ARC	Material extrusion	Metal		Metal	9–West
NAVSEA	NSWC, Corona	WC/SC/Lab	GE	Dual Laser M2 Cusing V4	Powder bed fusion	Metal	10 x 10 x 11	316L, 17–4PH need approval for Al and Ti	9–West
USMC	SPMAGTF-CR-CC	Field	MarkForged	Metal X	Material extrusion	Metal	9.8 x 8.7 x 7.9	17-4PH Stainless, H13 Tool Steel	International

APPENDIX G. SIMULATION MODEL PSEUDOCODE

This appendix offers a pseudocode explanation of the parameters and functions that comprise the operationalize AM simulation model. Additional fully developed simulation .py scripts, code by phase to call specific functions, adjustable input programs that simplify the running of the model and code to clean and analyze raw datasets are available from the author upon request. Email: Wes.shields@gmail.com.

a. Phase 1: Demand Generation

The first phase of the simulation is the order generation phase. In this phase, orders are received from customers and entered into the system. The following pseudocode delineates how each function fits into each of their respective phases, as well as the larger model as a whole. Many of the variable names contained within this pseudocode are remnants from the simulation model's construction, where dummy input parameters were employed to evaluate functionality of each function covered throughout this section.

Table 30. Phase 1 Input Parameters and Functions

Parameter Name	Category	Description	Associated Function(s)	Phase Called
Days	Instantiate Orders Per Day	Range of days covered by model	*Create_poission_sequence, Generate_demand*	Phase 1
Limit	Instantiate Orders Per Day	Total number of orders simulated during the test range	*Create_poission_sequence, Generate_demand*	Phase 1
Last_Day_Limit	Instantiate Orders Per Day	Limit on final simulation day, to keep each preceeding simulation day within parameters	*Create_poission_sequence, Generate_demand*	Phase 1
Lambda	Instantiate Orders Per Day	Mean number of orders from sample groups, forms Poisson Distribution	*Create_poission_sequence, Generate_demand*	Phase 1
quantity_range	Assign Quantities Per Day	Total range of order quantities to simulate	*Assign_Quantity, Generate_demand*	Phase 1
majority_range	Assign Quantities Per Day	Range of most probable order quantities to simulate	*Assign_Quantity, Generate_demand*	Phase 1
majority_prob	Assign Quantities Per Day	Probabilistic threshold to favor majority range	*Assign_Quantity, Generate_demand*	Phase 1
weights_dictionary	Simulate Weights	Simulated Weight Parameters and Probabilistic thresholds for each	*Build_weights_list, Generate_demand*	Phase 1
closed	SameDay OpenClose Percentage	Probabilistic threshold to simulates orders fulfilled via local inventory	*Generate_demand*	Phase 1
still_open	SameDay OpenClose Percentage	Probabilistic threshold to pass remaining orders to next phase	*Generate_demand*	Phase 1

(1) Create_poission_sequence

To initialize the synthetic demand generation, the `create_poission_sequence` function takes in a list of days range, the total number of orders the user is requesting the model simulate, and a limiter on the last day of the simulation, as to not have an exceeding large number of orders on the last day of the simulation range, forcing the demand generator to adhere to the distribution.

It then uses a random number generator to create a list of Poisson distributed random numbers. It appends the last value in the sequence to the list of numbers and checks if it is within the given limit. If not, it resets the trigger variable and continues generating numbers. Finally, the function returns a dictionary of empty lists where the key is the day number, and the value is the list of Poisson distributed random numbers for that day.

(2) Assign_Quantity

The model defines a function to assign a quantity range, a majority range, and a majority probability.

1. The `new_beginning` variable is set to the majority range's first value plus 1. The `choose_list` variable is set to a list of numbers that are generated by multiplying 100 by a list of x values from the `new_beginning` to the quantity range's first value.

2. The `zero_to_one`, `one_to_twofive`, and `twofive_to_four` variables are set to lists that will store the generated numbers. The `greater_than_four` variable is set to a list that will store the generated numbers.

3. The model loops through the `choose_list` and checks if the length of the number is greater than 4. If it is, the model adds the number to the `zero_to_one` list. If the length of the number is greater than 2, the model adds the number to the `one_to_twofive` list.

4. If the length of the number is greater than 1, the model adds the number to the `twofive_to_four` list. If the length of the number is not greater than 4, the model adds the number to the `greater_than_four` list.

5. A check of the random number occurs to evaluate if it is less than a user input probabilistic threshold value, and if it is, returns the choice from the list of numbers created in step 3. If the random number is not less than the user input probabilistic threshold value, an exponential function is employed to generate a random number.

6. If the generated number is less than the user input parameter, the choice from the list of ranges created in step 4 is returned.

8. If the generated number is greater than or equal to the prior user input parameter *x*, but less than a newly given user input parameter *y*, the choice from the list of ranges created in step 4 is returned.

9. If the generated number is greater than or equal to *y* but less than newly given user input parameter *z*, the choice from the list of ranges created in step 4.

10. If the generated number is greater than *z*, this line returns the choice from the list of ranges created in step 4.

(3) Build_weights_list

This function takes in a list of new data and creates a list of weights corresponding to each number in the new data. The values for weigh are assigned by the user, and function as binned categories.

(4) Generate_demand

1. The function sets a seed for the random number generator, then creates a list of weights using the `build_weights_list` function.

2. Function begins tracking how many trials have been performed.

3. For every order in the `one_hun_days` dictionary, the model assigns the corresponding day to the order and calculates the quantity ordered.

4. It then adds the *order id* and *weight* to a dataframe, and separates the dataframe into an *ID*, *day* column and a *weight* column.

5. Next, the model generates a list of random numbers using the Poisson distribution. The limit value indicating the target number of orders to be simulated is appended to the list.

6. The model then retrieves the last value in the list and checks if the last value is outside of the given limits. If it is, it resets the trigger variable and increments the count variable. Else, the model proceeds to the next iteration.

b. Phase 2

Table 31. Phase 2 Input Parameters and Functions

Parameter Name	Category	Description	Associated Function(s)	Phase Called
`Day_Splits`	Conditions for Print_Probability	List segmenting simulation day range into groupings by year	*Separate_Print, Isolate_Print*	Phase 2
`probs_w_print`	Conditions for Print_Probability	Probabilistic thresholds considering orders for AM. Deterministic	*Isolate_Print*	Phase 2
`print_prob`	Conditions for Print_Probability	Probabilistic thresholds orders are sourced to the respective print node	*print_assign_day, create_print_list*	Phase 2
`print_list`	Conditions for Print_Probability	List of print node names	*create_print_list, assign _print_days, df _Add_print_days*	Phase 2
`print_dict`	Conditions for Print_Probability	Print time day ranges and probabilistic threshold of print failure	*print_assign_day, assign _print_days, df _Add_print_days*	Phase 2

(1) Separate_Print

1. This function creates a list of *True* and *False* values, with *True* representing the dataframe that will be printed and False representing the dataframe that will not be printed.

2. It then loops through all of the data in the dataframe, checking the *Weight* column to see if the value is *z*. If it is, then the dataframe will not be printed and *False* is appended to the `Print_Vec` list.

3. Then the model checks if the Weight column is a user defined parameter *x* and the *`Quantity_Ordered`* column is greater than a user defined integer. If both conditions are met, then the dataframe will not be printed, and *False* is appended to the `Print_Vec` list.

4. This line checks if the Weight column is *y* and the `Quantity_Ordered` column is greater than *z*. If both conditions are met, then the dataframe will not be printed. *False* is appended to the `Print_Vec` list.

5. If the conditions in steps 2–4 are not met, then the dataframe will be printed (*True* is appended to the `Print_Vec` list).

6. The model separates the two dataframes, with the dataframe that will not be printed becoming `Phase2_3` and the dataframe that will be printed becoming *Print*.

(2) Isolate_Print

1. Takes the print-capable dataframe *Print* and winnows out the ID's that will not be printed.

2. Creates a list of True and False values, where *True* indicates that the day value is greater than the `Day_Splits` value and *False* indicates that it is not

3. Appends the True/False values to a list, and returns the list

(3) Create_print_list

1. This function creates a list of choices for the print node list by iterating through the `print_prob` list and creating a list of lists, where each list corresponds to a `print_prob` value. For example, the first list in the created list will be the list of choices for the print node when the `print_prob` value is 0.

2. It then creates a list of selections from the list of choices created in step 1

3. The model then creates a list of selections from the list of choices created in step 1. The list of selections is created by using the *itertools.chain* function to combine each list in the created list.

(4) Print_assign_day

1. A function called `print_assign_day` is defined by taking two arguments: the first being the value of a print node, and the second a dictionary of probabilities for a reprint and days to print.

3. The `first_choice` variable is set to the value of the choice node, which is randomly selected from the dictionary of probabilities.

4. The *rando* variable is set to a random number. If the random number is greater than the probability for a successful print, the `first_choice` variable is doubled.

6. The function returns the `first_choice` variable.

(5) Assign_print_day

1. The model creates a function that assigns a list of days to a node

2. The function takes a list of days and a dictionary of print instructions as input

3. The function then assigns the node a day using the print instructions from the dictionary, then returns the node and the assigned day

(6) Df_add_print_days

1. The model defines a function that takes a dataframe, a list of print nodes, and a dictionary of print node information as arguments.

2. The function creates a copy of the dataframe, assigns a list of empty nodes to the *`Node`* column, and sets up an empty list to store the added days.

3. The function then applies the function `assign_print_days` to the list of print nodes and the dictionary of print node information. The function evaluates a print node and a dictionary of information as arguments and assigns the information to the print node.

4. The function `assign_print_days` creates a tuple of the form (print node, information).

5. The function evaluates a dataframe and a function as arguments. This function then applies the function `assign_print_days` to each element of the dataframe *test*.

6. The function `drop` drops a column from a dataframe. In this case, it drops the *Test* column from the dataframe *test*.

c. *Phase 3*

Table 32. Phase 3 Input Parameters and Functions

Parameter Name	Category	Description	Associated Function(s)	Phase Called
non_print_nodes	Probabilities for Each Subset of Nonprint Distribution Nodes	List of non-print node simulated distribution center names	assign_node_day, df_Add_node_days	Phase 3
subset1	Probabilities for Each Subset of Nonprint Distribution Nodes	Grouping of simulated closest to customer distribution center nodes	df_Add_node_days	Phase 3
prob_1	Probabilities for Each Subset of Nonprint Distribution Nodes	Probabilistic thresholds orders are distributed to nodes in subset1	assign_node_day	Phase 3
subset2	Probabilities for Each Subset of Nonprint Distribution Nodes	Grouping of simulated next closest to customer distribution center nodes	df_Add_node_days	Phase 3
prob_2	Probabilities for Each Subset of Nonprint Distribution Nodes	Probabilistic thresholds orders are distributed to nodes in subset2	assign_node_day	Phase 3
subset3	Probabilities for Each Subset of Nonprint Distribution Nodes	Grouping of simulated furthest from customer distribution center nodes	df_Add_node_days	Phase 3
prob_3	Probabilities for Each Subset of Nonprint Distribution Nodes	Probabilistic thresholds orders are distributed to nodes in subset3	assign_node_day	Phase 3
Split_1	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 21 - 90 days, remaining orders sent to Split_2	Phase_3_splits	Phase 3
Split_2	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 91 - 365 days, remaining orders sent to Split_3	Phase_3_splits	Phase 3
Split_3	NonPrint Nodes adding days simulating lead time	Probabilistic threshold for orders filled 366 - 1000 days, remaining output as "lost.csv"	Phase_3_splits	Phase 3

(1) Assign_node_days

1. This code defines a function called `assign_node_day` which takes three parameters–`nodes`, `subset_list`, and `p_list`.

2. The function assigns a randomly chosen node to a day list. For every item in the subset list, the function checks if the assigned node is in that list.

4. If the node is in the list, the function assigns a random day from the corresponding list to the node.

(2) Add_node_days

1. The function `df_Add_node_days` is defined with the *df* variable copied by using the copy() functionality.

3. The *Test* column is created using the apply() functionality. The column is created by applying the assign_node_day() function to the `nodes`, `subset`, and `p_days` variables.

4. The *Node* column is created using the apply() function. The column is created by applying the function to the Test column.

5. The *`Added_Days`* column is created using the apply() function. The column is created by applying the function to the Test column.

d. Phase 4

Table 33. Phase 4 Input Parameters and Functions

Parameter Name	Category	Description	Associated Function(s)	Phase Called
p_Bin_A	Added Days simulating transportation time	Assign binary probability that order falls into transportaiton mode A	*Add_Bin_Days*	Phase 4
weight_condition	Favors transportation mode based on order weight	Sets probabilistic thresholds based on orders weigh for transportaiton mode A or B	*Add_Bin_Days*	Phase 4
Bin_A	Added Days simulating transportation time	Transportation mode A day range	*Add_Bin_Days*	Phase 4
Bin_B	Added Days simulating transportation time	Transportation mode B day range	*Add_Bin_Days*	Phase 4

(1) Add_Bin_Days

1. The model defines a function called Add_Bin_Days, that takes in four parameters: a dataframe that is to be manipulated, `bin_a_p`-the lower bound of the bin for the first variable, `weight_condition`-a condition that determines whether or not a row should be included in the bin, and `Bin_A_list`-a list of bin boundaries for the first variable.

2. The model loops through all the rows in the dataframe. For each row, it calculates the probability value for the given `weight_condition`.

3. If the p-value is less than `bin_a_p`, then the row is included in the *True* vector.

4. If the p-value is greater than 1- `bin_a_p`, then the row is included in the *False* vector.

5. The model then creates a list of *True* and *False* values, one for each row in the dataframe.

6. The model assigns a *True* or *False* value to the *T_F* vector list based on whether the *Weight* column in the dataframe is in the `weight_condition` list.

7. The model applies a function to each row in the dataframe, splitting it into a list of *True* and *False* values, and sorts the list of *True* and *False* values by the *Day* column.

8. The model adds the *Day_Completed* column to the *Merged* dataframe, which is the sum of the *Day*, *Added_Days*, and *Last_Mile_Days* columns.

7. The *True* and *False* vectors are then converted into a NumPy array.

8. The *Bin_A* and *Bin_B* variables are set to the corresponding rows in the dataframe.

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