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ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

Using Additive Manufacturing to Mitigate the Risks of Limited Key Ship Components of the Zumwalt-Class Destroyer

December 2016

LT Xiao Y. Wang, USN

LCDR James R. Whitworth, USN

Thesis Advisors: Dr. Charles Pickar, Senior Lecturer
Raymond Jones, Full Time Faculty

Graduate School of Business & Public Policy

Naval Postgraduate School

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ABSTRACT

The purpose of this project was to explore the benefits of using a combination of additive manufacturing (AM), Performance-Based Logistics (PBL), and Open Systems Architecture (OSA) to mitigate the risks of limited key ship components for the Zumwalt-class destroyer (DDG 1000) program. Specifically, this project was focused on current industry's capability for AM and the implementation of AM in the near future. Research was conducted in three phases. First, this research reviewed the problems and challenges within the defense industry. Next, this research reviewed the previous research on intellectual property (IP) concerns with AM (particularly, insourcing versus outsourcing) and the latest AM applications in the marketplace and defense industry. Finally, this research focused on DDG 1000 program documents, including the Acquisition Strategy (AS), the Life-Cycle Sustainment Plan (LCSP), and a Diminishing Manufacturing Sources and Material Shortages (DMSMS) analysis. By conducting a comparison of DDG 51 and DDG 1000 and analyzing an AM arrangement among Airbus, Systemanalyse and Programmentwicklung (SAP), and United Parcel Service (UPS), this research concludes that the government can use AM, with a properly structured PBL arrangement and OSA, to substantially mitigate risks, lower operation and support (O&S) costs, and effectively improve system readiness.

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—LT Xiao Wang

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Finally, I want to extend a thank you to my thesis partner, LT Xiao Wang, for his patience and diligence toward making sure we achieved this goal.

—LCDR Jim Whitworth

ABOUT THE AUTHORS

Xiao Wang, Lieutenant, is a Supply Corps Officer, enlisted in the Navy in 1999 and commissioned through the Officer Candidate School program in 2007. He earned a Bachelor of Science degree in Professional Aeronautics from Embry-Riddle Aeronautical University in 2006. Prior to his officer career, Lieutenant Wang was assigned to Electronic Attach Squadron One Three Six, Atsugi, Japan and Strike Test Squadron Two Three, Patuxent River, Maryland. At sea, Lieutenant Wang served as Aviation Depot Level Repairable Officer aboard USS Dwight D. Eisenhower (CVN 69) and Supply Officer aboard USS LABOON (DDG 58). Ashore, he served as an aircraft procurement budget analyst at Naval Air System Command (NAVAIR), Patuxent River, Maryland and completed a GSA tour as the J4 Logistics Officer in Baghdad, Iraq. Lieutenant Wang is currently pursuing his Master of Business Administration in Contracting and Acquisition Management. He is happily married to his wife Li and a devoted father to his young daughters Angela and son Alex. Upon graduation in December 2016, he is reporting to Bahrain as the Assistant Operation Officer of Combined Task Force (CTF) - 53.

James Whitworth, Lieutenant Commander, is a Supply Corps Officer, commissioned through the Limited Duty Officer program in 2006. He earned a Bachelor of Science degree in Resource and Technology Management from Troy University in 2011. While enlisted he completed sea duty assignments aboard USS ANZIO (CG 68), USS DETROIT (AOE-4), and USS THEODORE ROOSEVELT (CVN 71) performing myriad duties. He also completed shore assignments at Navy Passenger Transportation Office, Naples, IT; Weapons Department, Naval Air Station Sigonella, IT, and Barracks Manager, Naval Air Station Whidbey Island, WA. He has completed tours as an officer aboard USS ABRAHAM LINCOLN (CVN 72) and USS AMERICA (LHA 6) as well as a tour as an instructor at the Aviation Maintenance Officer School, Milton, FL. He is married to Karen and they have two children. After graduation in December 2016, he will report to the Fleet Readiness Center Southwest, NAS Coronado, CA as the Comptroller.

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three Dimensional
3DCD	Three-Dimensionally Printed Circuit Devices
3DLST	Three-Dimensional Laser Scanning Technology
3DP	Three-Dimensional Printing
AAW	Anti-Air Warfare
ACAT	Acquisition Category
AGS	Advanced Gun System
AM	Additive Manufacturing
AMDR	Air and Missile Defense Radar
AMF	Additive Manufacturing File
Ao	Operational Availability
AS	Acquisition Strategy
ASD	Assistant Secretary of Defense
ASN	Assistant Secretary of the Navy
AT/FP	Anti-Terrorism/Force Protection
AT&L	Acquisition, Technology, and Logistics
ATP	Advanced Turboprop Engine
BAE	British Aerospace
BIW	Bath Iron Works
BMD	Ballistic Missile Defense
CAD	Computer-Aided Design
CASREP	Casualty Report
CDSA	Combat Direction Systems Activity
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
CO2	Carbon Dioxide
COTS	Commercial-Off-The-Shelf
CPAF	Cost Plus Award Fee
CPIF	Cost Plus Incentive Fee
CPLM	Collaborative Product Lifecycle Management
CRS	Congressional Research Service

DAS	Data Acquisition Strategy
DC	Damage Control
DDG	Navy Destroyer
DFARS	Defense Federal Acquisition Regulation Supplement
DMS	Data Management Strategy
DMSMS	Diminishing Manufacturing Sources Material Shortages
DOD	Department of Defense
DON	Department of the Navy
DOT&E	Director, Operational Test and Evaluation
EBAM	Electron Beam Additive Manufacturing
EOL	End of Life
ERP	Enterprise Resource Planning
FAR	Federal Acquisition Regulation
FCCOM	Facilities Capital Cost of Money
FDM	Fused Deposition Modeling
FPIF	Fixed Price Incentive Fee
FRP	Fibre Reinforced Plastic
GAO	Government Accountability Office
GE	General Electric
HII	Huntington Ingalls Industries, Inc.
IP	Intellectual Property
iPDA	improved Power Distribution Assembly
IPT	Integrated Product Team
ISE	In-Service Engineering
JIM	Just-in-Time Manufacturing
LCC	Life-Cycle Costs
LCSP	Life-Cycle Sustainment Plan
L&MR	Logistics & Materiel Readiness
LON	Life of Need
LRU	Line Replaceable Unit
LTB	Life of Type Buy
MCAS	Marine Corps Air Station
MCC	Major Contracting Command

MOSA	Module Open System Approach
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NDI	Non-Development Item
NICN	Navy Item Control Number
NSFS	Naval Surface Fire Support
NSWCCD-SSES	Naval Surface Warfare Center, Carderock Division–Ship Systems Engineering Station
NSWCDD	Naval Surface Warfare Center, Dahlgren Division
NUWC	Naval Undersea Warfare Center
OMIS	Obsolescence Management Information System
OOC	Out of Commission
O&S	Operating and Support
OSA	Open System Architecture
PBL	Performance-Based Logistics
PCB	Printed Circuit Board
PEO	Program Executive Office
PM	Program Manager
PMS	Planned Maintenance System
PN	Part Number
PRECOM	Pre-Commissioning
PS	Power Supply
PSM	Product Support Manager
RBS	Readiness-Based Spare
RD&A	Research, Development, and Acquisition
RMC	Regional Maintenance Center
ROI	Return On Investment
SAP	Systemanalyse and Programmentwicklung
SECDEF	Secretary of Defense
SECNAV	Secretary of the Navy
SL	Stereolithography
SOS	System of Systems
STL	Stereolithography File Format

TLCSM	Total Life Cycle Systems Management
TSCE	Total Ship Computing Environment
UPS	United Parcel Service
USD	Under Secretary of Defense
UV	Ultraviolet

EXECUTIVE SUMMARY

Zumwalt-class destroyer (DDG 1000) is a three-ship program that represents the pinnacle of state-of-the-art technology. Because of technologies, intellectual properties, and scale economies, DDG 1000 is in a sole-source, or limited sources, acquisition environment. The risks associated with a limited supplier base could threaten the part support on many key ship components and the overall performance of its service life for the next 25 years or more. For cost saving purposes, all three ships will have a homeport in San Diego, CA, where organic repair, off-ship maintenance, and performance-based logistic support take place. The DDG 1000 program is also facing budget cuts, program cost growth, and competition from other classes of ships; therefore, Program Executive Office (PEO) Ships and the DDG 1000 program office must find ways to mitigate the risks of key ship components and enhance system performance with a sound life-cycle sustainment strategy.

Traditional approaches for operating and maintenance are accomplished with organic repair capabilities or contracted services. Due to the technology complexity and existing organic capabilities, a combination of organic support and performance-based logistics (PBL) has been identified as part of DDG 1000's life-cycle sustainment plan. Regardless of the approaches, either the government or the chosen PBL providers will have to tackle the obsolescence issues and address the issues associated with a limited supplier base. Traditionally, the decision-maker will have to decide on either a lifetime-buy or bridge-buy decision, based on industry data and the obsolescence management forecast, and anticipate failure rates to ensure that the needed parts are available for the operation and support of the systems. The advent of additive manufacturing (AM) and recent technology advancement can eliminate the need for a lifetime or bridge-buy decision, reduce ship's operating and maintenance costs, and innovative enhance system performance. Research on AM developments is used to identify capability gaps and explore opportunities for improving system readiness.

In order to introduce AM as part of the solution, this project first examined the benefits and limitation of PBL and assessed the competition requirement for federal acquisition strategy and the challenges in obsolescence management. This project then verified that PBL and OSA are part of DDG 1000's acquisition strategy, as they are the prerequisites for entering a contractual agreement with contracted service providers for Operation and Support (O&S) and enabling system interoperability. This project subsequently compared operating and support characteristics between Arleigh Burke–class (DDG 51) and Zumwalt-class (DDG 1000) ships and assessed the ability of the Department of Defense (DOD) to expand DDG 1000's logistic support footprint similar to the arrangement among Airbus, Systemanalyse and Programmentwicklung (SAP), and United Parcel Service (UPS).

The purpose of the study was to research the latest AM developments within the commercial marketplace and defense industry and explore the ways that AM can help to drastically reduce the risks of limited key ship components. The project answered the following questions:

- How should the government structure PBL contracts that will incentivize the use of AM?
- If the government decides to insource, what are the considerations in make-or-buy decisions?
- How can the DDG 1000 program leverage the capabilities of AM for its existing and future requirements?

Primary research data was provided by the Zumwalt-class Program Office (PMS 500). Secondary research was collected from public resources. Based on the findings of this research, it is imperative to have AM, properly structured PBL arrangements, and well thought-out OSA strengthen each other and mitigate the risks of limited key ship components that are associated with their supplier base. Naval Undersea Warfare Center (NUWC), PMS 500, and contractors could jointly identify parts as candidates for AM solutions. PMS 500 should also engage other DOD agencies on AM capacities and request information from defense contractors on their planned use of AM capabilities for part support.

I. INTRODUCTION

A. BACKGROUND

The construction and sustainment of today's complex Navy ships requires numerous key military-unique components with diminishing manufacturing sources and material shortages. Program managers (PMs) must aggressively address risks associated with parts that face obsolescence (Assistant Secretary of the Navy for Research, Development, and Acquisition [ASN(RD&A)], 2016b). The Zumwalt-class destroyer (DDG 1000) is a technology-laden ship whose production has been limited to three vessels due to the increased cost in technology development, changes in the U.S. Navy's mission environment, and fiscal budget constraints. Within the DDG 1000 system of systems (SOS), there is usually one contractor for a particular system, and many end items are sole sourced, have limited numbers of suppliers, or face obsolescence in the near term.

The current acquisition strategy of DDG 1000 has listed Open Systems Architecture (OSA) as a design concept and Performance-Based Logistics (PBL) for its operation and support (O&S) structure, which mirrors the strategy for the Arleigh Burke class (DDG 51). While OSA and PBL can help to mitigate some of the supplier risks by allowing future suppliers to participate in DDG 1000's system upgrade and leveraging PBL contractors' expertise and resources in O&S, these two approaches alone will not necessarily mitigate the risks associated with a limited supplier base. OSA promises future upgrade possibilities; however, research and development (R&D) has a price tag, and it is not the first alternative to mitigate the risk of O&S support. PBL allows the government to transfer some of the obsolescence management responsibility to contractors; however, without the adequate performance metrics, incentives, and resources, PBL can still fail to satisfy the warfighter's requirement and become unaffordable.

The government does have some organic capability to produce and repair some items in-house; however, the costs associated with intellectual property (IP) rights can limit the usage of this option. Organic support also requires the government to make lifetime or bridge-buy decisions, provide job specific training, and maintain the needed expertise and resources. Additive manufacturing (AM) has become a more mature technology in 2016 and has advanced across many industries and domains, making AM a viable means in mitigating the risks identified in this section. This report examines the DDG 1000 program with regard to its unique systems and a small total production quantity, and explores the areas where AM, PBL, and OSA can jointly add value to the program performance, mitigate risks of limited suppliers, and reduce O&S costs.

1. History of the DDG 1000 Program

The DDG 1000, or Zumwalt-class destroyer, program was established to become one of the next-generation surface combatants for the Navy. This program replaced the DD(X), formerly known as DD-21, as a new Future Surface Combatant project (O'Rourke, 2009). As the report also points out, this destroyer was intended to provide naval surface fire support (NSFS) and the ability to operate in littoral waters. This new destroyer, however, could not meet some of the requirements the current DDG 51 class is capable of, such as ballistic missile defense (BMD) and anti-air warfare (AAW), mainly due to the program office's decision to replace the SPY-4 Volume Search Radar (VSR) as a result of the program's excessive cost overrun resulting in a Nunn-McCurdy legislation breach (O'Rourke, 2009). The Nunn-McCurdy legislation under U.S. Code Title 10 requires the DOD to take positive action when a major defense acquisition program breaches statutory cost-growth thresholds or face program termination (O'Rourke, 2016). Many new technologies are incorporated into the operation and design of DDG 1000, which, as of late 2016, will remain unique and specific to this class of ship. Until some of these new technologies are incorporated into future ship designs, such as the Arleigh Burke DDG 51 class, the Independence class, or the Freedom-class littoral combat ship (LCS), the support will suffer from a lack of economy of scale and limited parts supply.

The design of DDG 1000 incorporates automated technology to lower O&S cost by reducing its crew size to 142 sailors, a 50% reduction in manpower compared to the Navy's Aegis destroyers and cruisers (O'Rourke, 2016). The automated system, the Ship Control System (SCS), will allow the crew to remotely monitor and control the navigation, hull, electric plant, machinery plant, and damage control functions (ASN [RD&A], 2016a). The DDG 1000 class is approximately 63% larger than any Navy destroyer or cruiser in the fleet as of late 2016 (O'Rourke, 2016). In this sense, the DDG 1000 class has a smaller group of sailors to monitor and operate a greater amount of complex, automated equipment on a much larger platform. One of the many requirements to operate a DDG 1000 class with this small-sized crew is reliable systems with adequate parts support for operational availability.

The original acquisition plan called for the procurement of 32 ships, which would have allowed a normal support strategy. The program went through myriad procurement changes that reduced the total ship quantity to 24, then to 16, then to seven, before finally settling on a total of three ships in the Fiscal Year (FY) 2011 budget (O'Rourke, 2009). Figure 1 provides an overview of the program history.

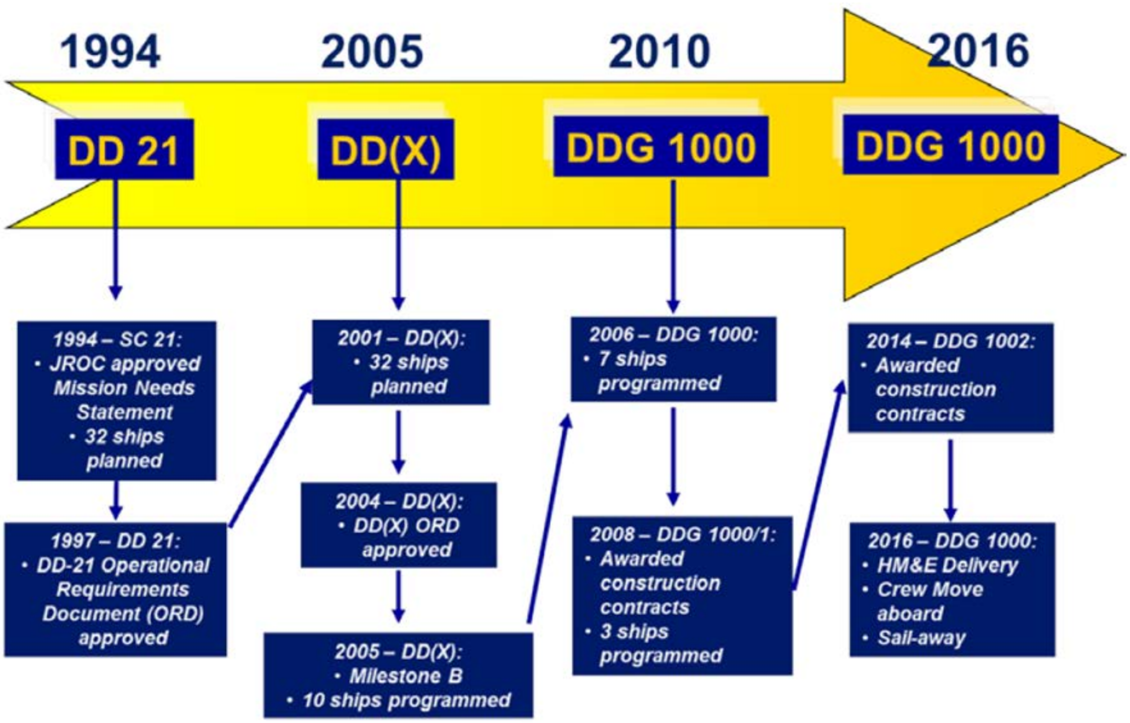

Figure 1. DDG 1000 Program History. Source: Program Executive Office (PEO) Ships (2016).

The cost growth affecting the DDG 1000 program stems from the reduction in total ships, and the procurement-rated costs are distributed among fewer ships (O'Rourke, 2016). This outcome resulted in a Nunn-McCurdy cost breach, in which congressional approval is required to continue a program that has experienced extreme cost growth (O'Rourke, 2016). There are secondary and tertiary effects beyond the immediate cost increase on system R&D,

ship construction, and system acquisition. Those impacts on the overall program life-cycle cost might take years to quantify.

One of the victims of the cost breach is the SPY-4 Volume Search Radar (VSR), as it was removed from the DDG 1000 design with no replacement (O'Rourke, 2016). Through this cancellation, the Zumwalt program initially realized a savings of $300 million; however, the Gerald R. Ford (CVN 78)–class aircraft carriers had a cost increase of $54 million to continue with the integration of the VSR (O'Rourke, 2016). It is important to note that the unit price increases as the procurement quantity decreases and the O&S cost also increases accordingly. As shown in the VSR example, the reduction in the DDG 1000 production and the elimination of key systems might have affected not only the procurement cost and O&S cost of the DDG 1000 program, but also other programs/platforms.

2. New Technologies

The new ship design is noticeable from the first look. The DDG 1000 has a hull that slopes inward from the waterline up, in what is referred to as a tumblehome design, to reduce detection from adversaries (O'Rourke, 2016). The first two ships in the class, DDG 1000 and 1001, will also have superstructures made partly of large sections of composite (i.e., fiberglass-like) materials rather than steel or aluminum, while the final ship will implement construction of the superstructure with other material (ASN[RD&A], 2016a). These design ideas are completely different from any ship in the Navy's current inventory. Due to cost increases and program budget cuts, a steel deckhouse is reserved for DDG 1002 because the program office could not obtain a fair and reasonable price with Huntington Ingalls Industries, Inc. (HII; ASN [RD&A], 2016a). Unless the Navy can identify a second supplier for competition, or HII can drastically achieve cost-saving in its manufacturing process with the use of a composite material, a composite deckhouse is out of the decision-making horizon for future shipbuilding.

The Integrated Power System (IPS) that has been introduced into DDG 1000 makes it the first surface combatant in the U.S. Navy that uses all-electric architecture as a means of providing both power and propulsion to the entire ship (PEO Ships, 2016). The idea is that the main engines produce electricity that is sent to switchboards for further distribution throughout the ship (O'Rourke, 2000). O'Rourke (2000) explained that this arrangement will allow diversion of electricity required for propulsion to other areas that require an immediate surge of energy, for instance, a weapon system, without greatly affecting the speed of the vessel. PEO Ships (2016) identified that this system will be supported by the Navy and Defense Logistics Agency (DLA).

The ship's multi-function radar (MFR), AN/SPY-3(V)1, is the primary radar for Integrated Air and Surface Dominance, which requires power from the AN/SSA-29 Common Array Power System (CAPS) and cooling from the HD-1246/SPY Common Array Cooling System (CACS; PEO Ships, 2016). The primary radar for navigation and surface surveillance has remained the AN/SPS-73; while not new, this radar—like the new AN/SPY-3(V)1—has limited support (PEO Ships, 2016). AN/SPS-73 is a legacy surface search radar that has fleet-wide installation on most of the surface ships.

The Zumwalt will incorporate two new major weapon systems into its arsenal. The first is unique to the class, the MK51 Gun Weapon System, a 155mm Advanced Gun System (AGS) that will fire the Long-Range Land Attack Projectile (LRLAP; PEO Ships, 2016). This weapon exceeds the current capability of the MK45 5-inch gun for NSFS. The other is the MK57 MOD0 Vertical Launch System (VLS), similar in concept to the MK41 VLS, but with greater capacity in each tube for larger missiles and designed to be installed around the ship on the sides rather than in centralized magazines (PEO Ships, 2016). As noted in the Life-Cycle Sustainment Plan (LCSP), these systems are currently facing support issues (PEO Ships, 2016).

3. Design and Production Maturity

Despite the fact that the Navy accepted the first ship, USS *Zumwalt* (DDG 1000), the ongoing system and technology development may result in many design changes (Government Accountability Office [GAO], 2016). The GAO (2016) found that schedule delays were due to the challenges presented by electrical work, shipbuilder's resource shortages, and workforce turnover, as well as some significant technical issues related to the ship's hull, mechanical, and electrical (HME) systems. The GAO (2016) also estimated the initial operating capability (IOC) for the DDG 1000 is September 2018, which will result in a schedule delay of almost two years.

As shown in the DDG 1000's Milestone B Acquisition Strategy, dated April 26, 2016 (see Table 1), six of the 10 critical technologies are close but have not met the desired technology readiness level (TRL; ASN[RD&A], 2016a).

Table 1. DDG 1000 Critical Technology Scorecard. Source: ASN(RD&A) (2016).

	Critical Technology Area	TRL at MS B (Nov 05)	TRL at DAB (Oct 06)	TRL at TSS PRR (Oct 08)	TRL at MS B (Sep 10)	In Yard Date	TRL at Ship Installation
1	Advance Gun System and LRLAP	5	6	6	6	FY 11/13	6
2	Integrated Power System (IPS)	5	6	6	6	FY 09	6
3	Dual Band Radar Suite – MFR (SPY-3) / VSR	6/5	7/5	7/6	7/6	FY 10	7/6
4	Total Ship Computing Environment (TSCE)	5	5	5	6	FY 12	6
5	Peripheral Vertical Launching System (PVLS)/ Advanced Vertical Launching System (AVLS)	5	6/6	6/6	6/6	FY 08/ FY 11	7/6
6	Integrated Deckhouse and Apertures	5	6	6	6	FY 11	7
7	Hullform	6	6	6	6	FY 09	6
8	Infrared Signature Mock-ups	6	6	6	6	FY 10	6
9	Autonomic Fire Suppression System (AFSS)	6	7	7	7	FY 09	7
10	Integrated Undersea Warfare System (IUSW)	5	7	7	7	FY 10	7

4. Current Fleet Support Tactics

The current support tactics used by program managers (PMs) to support weapon systems revolve around performing either a lifetime buy or bridge buy to provide continuous support for the proposed life cycle of the equipment. Lifetime buys are configured to the proposed failure rates and life cycle of a weapon system (Sandborn & Goudarzi, 2015). Lifetime buys can be costly since the program typically purchases the support at the onset of a program and the cost is not spread over the life of the weapon system. According to Sandborn and Goudarzi (2015), bridge buys similarly are exercised to purchase parts until a proposed upgrade or new contract for support can be negotiated. The authors further explained that bridge buys are not necessarily as costly as lifetime buys but serve only to potentially prolong an obsolescence issue to a future date (2015).

The Navy's surface combatants typically have a service life of approximately 25 years; however, the current fleet has many surface combatants that have eclipsed the 25-year service life, and current projection and budget trends suggest that the Navy plans to maintain some destroyers for 40 years (Lewis, 2015). The unknown possibility of service life extensions adds to the difficulty of estimating the quantity of parts that should be purchased to provide support. When purchases are conducted to support the current service life, and this life is subsequently extended, the parts may not meet the requirements of the new extension. The Diminishing Manufacturing Sources and Material Shortages (DMSMS) guidebook provides a framework to analyze parts to determine obsolescence issues that can occur in order to understand the problems that will occur if parts support fails (ASN[RD&A], 2016b). The situation with DDG 1000 is exacerbated by the low number of total ships and the high number of the ship's unique systems that will not meet scale economies for suppliers.

Other cost additions that become part of the determination for purchasing parts are the penalties associated with under-buying or over-buying parts when executing the life-cycle buys. The penalty for under-buying, which is usually greater than that for over-buying, could have irrevocable effects when an extended length of service for a weapon system is conducted (Sandborn & Goudarzi, 2015). This could require expensive restructuring of manufacturing bases to begin a new support strategy for these systems if there is not a facility that already exists. The expense would result from a company beginning or retooling an assembly process.

While exploring purchasing options for lifetime or bridge buys, PMs must also account for minimum order quantities. These quantities are the lowest amount that a manufacturer will entertain when accepting a contract for parts, which is another complication that needs attention when determining the quantities of items to purchase to support the life cycle of a weapon system.

5. Summary

Supporting a program of record for its life cycle takes careful planning when not faced with abnormal obstacles. The decision to truncate the DDG 1000 program at three ships adds some complications that warrant discussion and new ideas on the support phase of these ships. While taking into account the problem of DMSMS, rightsizing the initial purchase of parts and looking to alternate methods of part production will be paramount to the weapon system sustainment. Lifetime buys require upfront information, accurate estimates, and substantial capital investment, which can make a program unaffordable and unexecutable. Moreover, advanced procured items face shelf life, obsolescence, and inventory issues. The return on investment (ROI) is not only difficult to quantify but also takes years or decades to realize. On the other hand, bridge buys can introduce tremendous risk in an unforeseeable operating and limited supplier base environment. Minimum order quantity, contracting lead time, and supplier capacity can delay the follow-on procurement and jeopardize system operation and support. Both lifetime buys and bridge buys can significantly increase DDG 1000 operating and support costs and negatively impact its mission readiness.

B. PROBLEM STATEMENT

The problem statement is as follows: the traditional approach to mitigating the risk of a limited supplier base has been primarily focused on making a lifetime/bridge-buy decision or insourcing the needed capabilities. Normally, the government prefers to have two or more suppliers, adequate competition, and the ability to maintain a strong industry base. However, the typical support structure for larger classes of ships will be difficult to attain because the DDG 1000 class has been truncated to three ships. In addition, the program office, PMS 500, which is responsible for the weapon system acquisition, could not possibly afford to procure all of the data rights early in the program, and the cost of obtaining the data rights later could effectively eliminate the insourcing option. As the Navy continues to work with its contractors to complete the first Zumwalt-class destroyer, DDG 1000, and the construction of DDG 1001 and 1002, current organic capabilities, PBL arrangement, and OSA design by themselves might not be able to mitigate the risks of a limited supplier base. Despite the fact that additive manufacturing (AM) has become a more mature process in 2016 and advanced across many industries and domains, the government has not yet investigated the possibility of using this revolutionary technology as a means to mitigate the limited supplier risk and improve the O&S support.

C. RESEARCH OBJECTIVES

The objectives of this research are to

- Evaluate the tradeoff, limitations, and benefits of using the PBL approach, OSA, and AM to mitigate the risks of diminishing suppliers.
- Understand the operating environment, the marketplace, and the defense industry.
- Identify whether the DDG 1000 program has all the prerequisites for the introduction of AM technologies.
- Determine the most beneficial arrangement to mitigate the risk of limited key ship components with properly structured PBL arrangements and incentives for the use of the most innovative AM technologies to provide support for DDG 1000.

D. RESEARCH QUESTIONS

With AM continuing to mature and advance across many industries and domains, making AM a viable means in mitigating the risks of limited key ship components.

- How should the government structure PBL contracts that will incentivize the use of AM?
- If the government decides to insource, what are the considerations in make-or-buy decisions?
- How can the DDG 1000 program leverage the capabilities of AM for its existing and future requirements?

E. PURPOSE / BENEFIT

Traditional approaches to addressing the DMSMS have been seeking organic life-cycle support, a PBL arrangement, or a combination of both. Regardless of the chosen approach, either the government program office or the PBL contractor who is responsible for the part support has to make the lifetime or bridge-buy decision. Since DDG 1000 is currently a three-ship program, traditional lifetime or bridge-buy decisions could be very expensive. With the introduction of AM, coupled with properly structured PBL contracts and an OSA, Program Executive Office (PEO) Ships can make timely and informed decisions in system support, upgrade, and expansion. Without the need to warehouse many low-volume, low-usage items and manage obsolescence, PEO Ships and individual contractors can now explore the benefits of just-in-time manufacturing (JIM), a benefit that

AM could offer. There is not a one-size-fits-all tool that will single-handedly solve the issues and mitigate risks. This research effort is intended to use a combination of techniques and approaches that can strengthen each to significantly lower the sustainment risks faced by the DDG 1000 program.

F. SCOPE AND METHODOLOGY

The scope of this research project is to determine alternate methods to provide weapon systems support to the DDG 1000 class of ships outside of the current lifetime buy or bridge-buy structure. First, the researchers collected secondary data from articles, scholarly journals, and government research reports of PBL, IP rights concerns associated with AM, competition concerns associated with insourcing, and obsolescence management to gain insight into the current strategy, process, and limitations in mitigating a limited supplier base. Next, the researchers investigated the current capabilities and future impacts of AM within the commercial marketplace and defense industry, as well as the AM applications with the Department of the Navy (DON). Then, the researchers analyzed the Acquisition Strategy (AS) and Life-Cycle Sustainment Plan (LCSP) of DDG 1000 to see if the program has an adequate environment for implementing AM. The researchers also analyzed the Navy Undersea Warfare Center (NUWC) Keyport's obsolescence analysis of DDG 1000's Improved Power Distribution Assembly (iPDA) circuit cards to present a new perspective on extending components' useful life and to mitigate the risk of a limited supplier base. This project then compared the operating environment between the DDG 51– and DDG 1000–class ships by identifying their similarities and differences. The researchers ended with the analysis of a recent arrangement among Airbus, Systemanalyse and Programmentwicklung (SAP), and United Parcel Service (UPS) to investigate the possibility of a similar setup for DDG 1000.

G. THESIS STATEMENT

The DDG 1000 program will require a unique structure for sustainment during the O&S phase of its lifecycle. The hypotheses for this research are as follows:

- Hypothesis 1: The DDG 1000 program can effectively mitigate the risks associated with limited supplier base for key Navy ship components by taking advantage of AM.

- Hypothesis 2: AM makes JIM for many critical components a reality and largely eliminates the need for a lifetime buy, which enables the government to shift its focus from manufacturing in-house to managing the support service.
- Hypothesis 3: Coping with properly structured PBL contract and OSA design, AM can also offer rapid design prototyping and system upgrading, making it easier to upkeep, update, and upgrade DDG 1000.

H. REPORT ORGANIZATION

After this introduction, Chapter II covers a literary review of the different aspects of PBL contracts, AM uses and advances, mitigating IP rights problems, and determining a make-or-buy decision, all of which are research areas that are being concentrated on for this thesis.

Chapter III identifies how these approaches will fit within the DDG 1000 program. This report qualifies the results of research that was conducted for the program office for compatibility with the options that are being presented.

Chapter IV discusses the findings and recommendations as applied to the DDG 1000 program.

Finally, Chapter V discusses future research that will enhance this research and provide more cogent answers to the problem of life-cycle sustainment for the DDG 1000 program.

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II. LITERATURE REVIEW

This literature review section begins with a review of the PBL arrangement because PBL is part of the current support strategy for the DDG 1000 program. The terms Performance-Based Logistics, Performance-Based Approach, and Performance-Based Arrangement are used interchangeably within the government workplace, in the defense industry, and in this research paper. Even though PBL is a statutory requirement by law and spelled out in the Federal Acquisition Regulation (FAR), in order to incorporate AM as part of the requirement, the federal government needs to structure the incentives to motivate contractors and have the proper metrics for performance oversight. The next part of this chapter is a discussion of the history, principles, techniques, and challenges of AM. Since many contractors have long been concerned with their intellectual property (IP) rights, this literature review delves into contractual concerns regarding patents, copyrights, and data rights related to AM. Next is an analysis of the research for a make-or-buy decision for parts that support the current maintenance of the U.S. Navy fleet and a discussion of the impact that insourcing has on the defense industry and the commercial marketplace. The research cites the FAR, the Defense Federal Acquisition Regulation Supplement (DFARS), and applicable articles that apply to government policies and socioeconomic concerns related to the health of the U.S. defense industrial base and the importance of maintaining a viable defense industrial base. This review section uses a specific part obsolescence case to show that PBL and organic capability alone cannot help to mitigate the potential risk in O&S support. Lastly, this section covers the latest industrial initiatives, the current state of AM technology, and the potential and future application of AM.

A. PERFORMANCE-BASED LOGISTICS (PBL) SUPPORT

PBL is not an option for offloading government responsibility on contractors. PBL is intended to augment the expertise, management, and resource needs of the government. In obsolescence management and part support, regardless of who is accountable for the make-or-buy decision, both the government and the chosen PBL contractor must come up with the business strategy to mitigate potential shortfalls and maintain optimal material availability and operational readiness.

Geary and Vitasek's (2008) research found that the DOD began to use PBL as a means to improve system readiness in 1999. Although it was not the first, Lockheed Martin (LM) was the prominent PBL contractor for providing support service to the Air Force's F-117 Nighthawk stealth aircraft during this period (Geary & Vitasek, 2008). The Navy kicked off its PBL effort as the ASN(RD&A) issued a PBL guidance document in 2003 and directed the Navy and Marine Corps to implement PBL on all new weapon system acquisitions and all Acquisition Category (ACAT) I and ACAT II systems in service (ASN [RD&A], 2003). Since then, PBL has become the default consideration for logistics support planning for the DOD. As time fast-forwarded, PBL is now a means to satisfy warfighter requirements, maintain system reliability and material availability, reduce O&S costs, and encourage innovation (Assistant Secretary of Defense for Logistics and Materiel Readiness [ASD(L&MR)], 2016).

In a 2005 *Defense Acquisition Review Journal* article, Berkowitz, Gupta, Simpson, and McWilliam pointed out that PBL is a tool to integrate defense system acquisition and sustainment. Their research explained that the government has expanded its focus beyond the near-term acquisition of weapon systems into the system sustainment, technology transfer, and defense industrial base as whole (Berkowitz et al., 2005). Moreover, the government is now responsible for the acquisition, sustainment, and disposal of major weapon systems, as well as their socioeconomic and environmental impact (Berkowitz et al., 2005). These researchers argued that it is important for the government to understand the benefits and limitations of PBL to maximize system performance. They concluded that even though the PBL approach can potentially offer benefits in reduced maintenance, operations, and support costs, along with improved customer wait time, enhanced combat readiness, and decreased obsolescence issues, the government and the chosen contractor still need to properly assign responsibilities, design performance metrics, incentivize the desired behaviors, manage risk-taking, and benchmark process improvement (Berkowitz et al., 2005).

Ewer (2015) conducted independent research in PBL approaches with the aim of helping PMs and Integrated Product Team (IPT) members to better understand the DOD policy and guidance and to properly employ PBL as a product support strategy. This research used a systems engineering approach to examine the six most current DOD policies and guidance of PBL implementation (Ewer, 2015). With his functional needs analysis, Ewer identified three major discrepancies: inconsistency between those PBL policy and guidance documents, program offices could not determine proper use of PBL, and documents do not provide sufficient PBL examples. Ewer (2015) argued that although a PBL approach can reduce the life-cycle cost, improve system reliability and availability, and minimize the logistics footprint, the government needs to provide clear and precise direction and guidance on PBL implementation.

Shortly after Ewer's (2015) research, the DOD issued the 2016 update of the PBL Guidebook to include additional lessons learned and implementation guidance (ASD [L&MR], 2016). The new 2016 update highlighted that PBL is not a one-size-fits-all tool and eliminated the confusion about whether PBL was mandatory. The 2016 PBL Guidebook also updated the Frequently Asked Questions section, added new material for IP consideration, refined data collection phase, and incorporated additional appendixes for pre-implementation check (ASD [L&MR], 2016). This 2016 release not only provided key insights of current PBL initiatives but also updated content for successful PBL implementation (ASD [L&MR], 2016). This new version of PBL was a huge step forward because it addressed many concerns and findings of Ewer's research and also clarified the ambiguity towards PBL arrangements.

As clearly stated in the 2016 PBL Guidebook, O&S costs account for 60%–75% of the total life-cycle costs (LCC) depending on the type of weapon system (ASD[L&MR], 2016). Moreover, until PBL emerged as a viable solution, the program office traditionally had a very limited ability to influence LCC once an acquisition was in its O&S phase. Therefore, in order to control LCC without jeopardizing the warfighter requirement, the DOD must carefully choose the proper contract type with performance-based arrangements and use adequate incentives to motivate the contractors for desired outcomes (ASD[L&MR], 2016).

Furthermore, a Proof Point study was chartered by ASD(L&MR) in 2010 to analyze the result of PBL on LCC (ASD[L&MR], 2016). Based on the comparison of PBL and non-PBL sustainment arrangements, the Proof Point study found that PBL arrangements not only reduced the costs but also improved system readiness if they were structured and executed properly. This Proof Point study found the following: 20 of 21 PBL arrangements showed performance improvement, and the only negative result was unrelated to its PBL arrangement; 70% of the PBL arrangements that adhered to the PBL tenets experienced cost and performance improvement; and three arrangements experienced cost increases because they were not structured to deliver savings (ASD[L&MR], 2016). A summary of the findings is provided in Table 2.

Table 2. Empirical Findings. Source: ASD(L&MR) (2016).

Empirical Findings
• Twenty of 21 programs studied experienced performance improvements, including three with very limited adherence to the generally accepted PBL tenets. ○ The 21st program's declining performance resulted from a part failing more than it was forecast; this situation was unrelated to the PBL arrangement and would have occurred in a non-PBL arrangement as well.
• Of the 21 programs, 15 programs had tenet adherence (where the cost impact was determinable with certainty) and experienced both cost and performance improvements.
• Three programs with very limited tenet adherence experienced cost increases. ○ None of the three programs were structured to deliver savings.

This Proof Point study also estimated that program offices can achieve an average annual cost saving of 5%–20% if they conform to the 10 key tenets listed in the 2016 PBL Guidebook (ASD[L&MR], 2016). These 10 tenets are summarized as follows: To be effective, PBL arrangements should have performance metrics that are outcome-based and relevant to the warfighter (ASD[L&MR], 2016). The guidebook states that these metrics are measurable, manageable, and capable of assessing the contractor's performance. PBL arrangements should include significant incentives to motivate performance in areas under the contractor's control. While Firm Fixed Price (FFP) contracts are the preferred contract type, Fixed Price Incentive Fee (FPIF) and Cost Plus Incentive Fee (CPIF) are also viable options for complex procurement. The government needs to ensure that the length of PBL contracts will help contractors recoup their investment costs. The government team and PBL contractors should jointly maintain their PBL knowledge and resources. The government leadership is crucial in creating an environment for successful PBL implementation. All stakeholders, from the top leadership to the lowest level of the workforce, should actively support the PBL arrangement. The Product Support Manager (PSM) should align and integrate supply chain activities to the desired PBL outcomes by reducing or eliminating internal stovepiped processes. Lastly, all participants should focus on total program risk reduction and share the risk management responsibility (ASD[L&MR], 2016).

Incentives, both financial and non-financial, are important for the successful implementation and execution of PBL arrangements. They are specifically addressed in the PBL Guidebook as the third and fifth tenets (ASD[L&MR], 2016). When it comes to the financial/monetary incentive, contracting officers can apply the Cost Efficiency Factor per DFARS 215.404-71-5 during a PBL contract negotiation. Specifically, contracting officers can use this special factor to motivate desired behaviors and encourage contractors to reduce costs by using innovative AM technology. Contracting officers can increase the contractor's profit by 4% when the contractor can clearly demonstrate its innovative approaches that lead to cost savings for the government. The evaluation criteria are whether the contactor participates in Single Process Initiative improvements, whether there is actual cost reduction on prior contracts, whether the contractor reduces or eliminates its excess or idle facilities, whether the contractor has cost reduction initiatives, whether the contractor has process improvements, whether the contractor helps its subcontractor to become cost efficient, whether the contractor effectively incorporates commercial items and processes, and whether the contractor invests in new facilities for better asset utilization and productivity (DFARS, 2015).

In addition, the contracting officer can use Facilities Capital Cost of Money (FCCOM) per FAR 31.205-10—Cost of Money—to reimburse the financial interest cost incurred by a contractor as long as those costs are measurable, assignable, and allocable to specific government contracts. If the contractor does not include FCCOM, the government will insert FAR 52.215-17—Waiver of Facilities Capital Cost of Money—to make it an unallowable cost under the contract. While many large defense contractors take advantage of the FCCOM reimbursement, small businesses and businesses that have not had any government contracts might not be aware of or have the needed information to request FCCOM as part of their contract negotiations. Cost of Money is an area where the government contracting officers can offer FCCOM to encourage the use of AM and compensate a contractor's capital investment in AM.

B. ADDITIVE MANUFACTURING (AM) TECHNOLOGIES

1. Additive Manufacturing

The modern day of AM is a process that uses Computer-Aided Design (CAD) software to create three-dimensional (3D) products by adding one layer on top on another layer to form an end item, which largely eliminates the traditional need for process planning, special tools, and setups (Gibson, Rosen, & Stucker, 2010). AM is fundamentally different from traditional manufacturing techniques that use cutting, molding, machining, and welding to create the desired shapes and properties. AM can form complex shapes that traditional subtractive manufacturing techniques cannot.

a. History and Development

The earliest form of AM was the cut and stack techniques used in topography and photosculpture almost 150 years ago, in which objects were formed manually by adding layers of individually cut material (Bourell, Beaman, Leu, & Rosen, 2009). Since layers had to be precut first, these primeval techniques are far different from modern day AM techniques that take advantage of sophisticated computer systems and CAD software.

A century and a half later, in 1987, 3D Systems, a prominent company that specializes in AM, launched the modern age of AM by introducing its stereolithography (SL) method—an AM process that "solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser" (Wohlers & Gornet, 2014, p. 1). Following the invention of SL, companies around the globe introduced a variety of AM techniques that continue to decrease costs year after year. Wohlers & Gornet (2014) pointed out that in 1996, 3D Systems sold its first 3D printer which used an inkjet printing mechanism to deposit wax material. In the same year, Stratasys, another leading AM company, introduced the Genisys machine with an extrusion process similar to its fused deposition modeling (FDM) technology (Wohlers & Gornet, 2014). By 2008, 12 years later, Stratasys unveiled its production-grade thermoplastic, ABS-M30i, a biocompatible FDM material for the food and drug industries (Wohlers & Gornet, 2014). By 2011, manufacturers of in-the-ear hearing aids adopted AM technology as their main production method for the custom-fit shells (Wohlers & Gornet, 2014). For the last 30 years, foreign and domestic organizations, universities, research labs, and for-profit companies have made significant progress in AM.

Today, after years of research, development, and integration, AM has blossomed in its ability to prototype parts and functional end-use products (Huang, Leu, Mazumder, & Donmez, 2015). CFM International, a 50/50 joint venture between GE Aviation and France’s Snecma, delivered the first two production models of the LEAP-1A engine, which contains 19 3D-printed fuel nozzles, to Airbus on April 2, 2016 (Kellner, 2016). Lockheed Martin teamed up with Sciaky Inc., a Chicago-based AM company, and used the Electron Beam Additive Manufacturing (EBAM) technique to produce a mission-critical titanium propulsion tank for its satellite program (Grunewald, 2016). These two most recent AM advancements are discussed in detail later in this chapter.

2. Principles and Technologies

Modern-day AM typically involves eight steps in a sequencing process: conceptualization and CAD, conversion to an Stereolithography File Format/Additive Manufacturing File (STL/AMF) file, transfer and manipulation of an STL/AMF file to the AM machine, machine setup, build, part removal and cleanup, post-processing of part, and application (Gibson et al., 2010). The first and foremost step is to have the CAD file, which is used to instruct an AM machine what to produce and which material to use. Depending on the material, technologies, and end-use, further cleanup, sanding, and processing might be necessary. While the concept for AM is quite common, the techniques and methodologies are different. Each AM technology has its advantages and disadvantages, primarily based on the material and end state. These differences are listed in Table 3.

Table 3. Additive Manufacturing Advantages and Disadvantages. Source: Cotteleer, Holdowsky, & Mahto (2014).

Technology	AM process	Typical materials	Advantages	Disadvantages
Stereolithography	Vat polymerization	Liquid photopolymer, composites	Complex geometries; detailed parts; smooth finish	Post-curing required; requires support structures
Digital light processing	Vat polymerization	Liquid photopolymer	Allows concurrent production; complex shapes and sizes; high precision	Limited product thickness; limited range of materials
Multi-jet modeling (MJM)	Material jetting	Photopolymers, wax	Good accuracy and surface finish; may use multiple materials (also with color); hands-free removal of support material	Range of wax-like materials is limited; relatively slow build process
Fused deposition modeling	Material extrusion	Thermoplastics	Strong parts; complex geometries	Poorer surface finish and slower build times than SLA
Electron beam melting	Powder bed fusion	Titanium powder, cobalt chrome	Speed; less distortion of parts; less material wastage	Needs finishing; difficult to clean the machine; caution required when dealing with X-rays
Selective laser sintering	Powder bed fusion	Paper, plastic, metal, glass, ceramic, composites	Requires no support structures; high heat and chemical resistant; high speed	Accuracy limited to powder particle size; rough surface finish
Selective heat sintering	Powder bed fusion	Thermoplastic powder	Lower cost than SLS; complex geometries; no support structures required; quick turnaround	New technology with limited track record
Direct metal laser sintering	Powder bed fusion	Stainless steel, cobalt chrome, nickel alloy	Dense components; intricate geometries	Needs finishing; not suitable for large parts
Powder bed and inkjet head printing	Binder jetting	Ceramic powders, metal laminates, acrylic, sand, composites	Full-color models; inexpensive; fast to build	Limited accuracy; poor surface finish
Plaster-based 3D printing	Binder jetting	Bonded plaster, plaster composites	Lower price; enables color printing; high speed; excess powder can be reused	Limited choice of materials; fragile parts
Laminated object manufacturing	Sheet lamination	Paper, plastic, metal laminates, ceramics, composites	Relatively less expensive; no toxic materials; quick to make big parts	Less accurate; non-homogenous parts
Ultrasonic consolidation	Sheet lamination	Metal and metal alloys	Quick to make big parts; faster build speed of newer ultrasonic consolidation systems; generally non-toxic materials	Parts with relatively less accuracy and inconsistent quality compared to other AM processes; need for post-processing
Laser metal deposition	Directed energy deposition	Metals and metal alloys	Multi-material printing capability; ability to build large parts; production flexibility	Relatively higher cost of systems; support structures are required; need for post-processing activities to obtain smooth finish

3. Benefits and Challenges

From the technology viewpoint, AM provides "unprecedented control over the shape, composition, and function of fabricated products, as well as a high degree of personalization for individuals" (Huang & Leu, 2014, p. 10). The DOD can significantly benefit from mass customization because DOD acquisitions usually do not require mass-produced items but small quantities of weapon systems and a variety of subassemblies (Huang et al., 2015). The DOD can use AM to satisfy rapidly changing needs at a mass production price, which is impossible to achieve in a traditional production environment with limited quantities (Huang et al., 2015). Many of DDG 1000's ship-specific items fall within this typical DOD acquisition profile—small quantity, yet a complex system.

While AM techniques have advanced significantly, many challenges remain: limitations in the choices of materials, process accuracy, consistency, qualification, and certification are some of the issues (Huang et al., 2015). AM parts may be made from similar materials; however, they may not all meet the standard material specifications because during the 3D printing process, small voids trapped inside can cause parts to fail under mechanical stress (Gibson et al., 2010). Gibson et al. (2010) also pointed out that most metal AM processes result in different microstructures due to rapid cooling. As a result, AM parts may have a better or worse property than conventionally manufactured parts (Gibson et al., 2010). The ultimate challenge for the AM industry is the ability to rapidly, efficiently, and inexpensively produce parts with 3D print technology, while at the same time, meet all functional requirements and certifications (Huang et al., 2015).

Traditional certification of equipment, materials, process, control, and personnel greatly limits the adoption of AM in a production environment (Huang et al., 2015). For large-scale AM parts, the challenge is to understand how the process affects the final product's material properties and performance (Huang et al., 2015). For certain military requirements, such as DDG 1000's propeller, the challenge is to meet those stringent standards under extreme conditions. For example, a 3D-printed propeller for a naval warship would need to pass the shock test and sustain a prolonged period of high-speed maneuvering.

In a September 3, 2015, memo, the Secretary of the Navy (SECNAV) specifically addressed the Chief of Naval Operations (CNO), Commandant of the Marine Corps (CMC), and ASN (RD&A) on the need to assist and facilitate AM implementation across the Department of the Navy (DON) enterprise (SECNAV, 2015). SECNAV (2015) viewed AM as a potential means to transform future maintenance, enhance logistics operation, improve self-sustainment during operations, and reduce total ownership costs because AM offers many advantages over traditional manufacturing.

The SECNAV tasked the ASN (RD&A) to coordinate and develop an integrated and detailed AM implementation plan by December 1, 2015, for the following:

- Increase development and integration of additive manufacturing systems.
- Develop the ability to qualify and certify AM parts.
- Standardize the digital AM framework and tools and enable end to end process integration.
- Establish the DON advanced integrated digital manufacturing grid.
- Formalize access to AM education, training, and certifications for the DON workforce.
- This plan will include the identification of an AM coordinator within ASN (RD&A), responsible for ensuring the execution of the above stated goals. (SECNAV, 2015, pp. 1-2)

4. Previous Research and Findings

Many researchers have studied various aspects of AM, including intellectual property (IP) concerns, insourcing options, competition, and obsolescence. This section includes an overview of those research areas.

a. Intellectual Property Concerns with AM

When it comes to additive manufacturing, the first thing that draws concerns and questions is intellectual property (IP) rights. With 3D scanning and AM, it is very feasible to re-engineer and recreate items that are identical to the original ones, which could trigger the IP rights infringement issue.

In Paben and Stephens's (2015) research, *Additive Manufacturing: An Analysis of Intellectual Property Rights on Navy Acquisition*, the authors focused on the potential impact AM might have on IP rights, government rights, and laws and regulations. Paben and Stephens first examined the statutory and regulatory laws related to IP for research analysis. Then they reviewed government data-rights standards, particularly within DOD and DON regulations and policies. Finally, the authors used a multi–case study analysis method to compare best IP management practices associated with AM in both private and public sectors.

In their research, Paben and Stephens (2015) cited specific rules, policies, and intellectual property clauses within the FAR and DFARS. They discovered that the DOD has issued numerous policies and handbooks for acquiring data since the early 1990s, with the intention of facilitating the formulation of a Data Acquisition Strategy (DAS) and Data Management Strategy (DMS) in defense system acquisition (2015). While the government is primarily concerned with different types of data rights and their associated costs of unlimited, limited, government-purpose restricted and other uses, industry's concerns with IP in AM revolve around sharing, accessing, manipulating, and altering a computer-aided design (CAD) file and the violation of IP rights (Paben & Stephens, 2015).

It is important to note that it has been the DOD policy, established by the USD (AT&L), to use of performance-based acquisition to minimize the need for data rights and limit procurement to truly needed data (OUSD[AT&L], 2001). The government also protect the subcontractors by prohibiting prime contractors from requiring subcontractors to relinquish their IP rights as a condition for award and using flow down contract clauses to afford subcontractor the same IP protection as the prime (OUSD[AT&L], 2001).

Paben and Stephens (2015) used the Napster case in the music industry to discuss potential IP rights issues with the use of CAD files and industry concerns of surrendering their IP to the government. Based on their findings, Paben and Stephens (2015) recommended that the DON proactively manage the requirement of IP data rights associated with AM as early as possible, preferably in the first stage of acquisition planning. They also stressed the importance of providing contracting officers with clear guidance and with contract clauses of AM requirements, the need for DOD instructions that incorporate the procurement of AM equipment and associated data rights, and the need to manage contractor expectations. Paben and Stephens (2015) concluded that the DON needs to be careful and vigilant in AM data rights procurement. They pointed out that the DON will negotiate the terms and conditions individually on 3D printing equipment and CAD files (Paben and Stephens, 2015).

If the government can afford the data rights and contractors are willing to surrender their IP rights, AM offers the opportunity to insource some manufacturing capabilities. The traditional approach tends to favor or mitigate logistics or sustainment risks though insourcing by expanding the government's organic capability. Insourcing gives the government more control and more certainty, such as on what to produce, how much to produce, and when to produce. Although insourcing might be a viable way to mitigate supplier-associated risks and reduce government spending on contracts, using an in-house approach is in conflict with maintaining a viable defense industry supplier base, meeting socioeconomic objectives, and encouraging innovation. The government itself is not in the manufacturing business.

b. Insourcing vs. Outsourcing

In *Make or Buy: An Analysis of the Impacts of 3D Printing Operations, 3D Laser Scanning Technology, and Collaborative Product Life Cycle Management on Ship Maintenance and Modernization Cost Savings*, Housel, Mun, Ford, and Hom (2016) analyzed the challenges in U.S. Navy fleet maintenance and modernization, explored the possibilities and potentials of AM, and recommended a phased implementation approach to gradually achieve a 100% insourcing goal for all required DON inventory parts based on their extensive and in-depth cost benefit analysis.

Housel et al. (2016) examined the complicated situation that the U.S. Navy currently faces: to properly maintain and keep operational a total of 288 ships in 12 ship classes and numerous variations within those classes based at over 10 homeports. They found that traditional ship maintenance and modernization tools and methods employ extensive acquisition processes, reverse engineering, and manufacturing of replacement parts when performed by outside contractors. Their research showed that insourcing contractor support operations with the use of 3D printing (3DP), 3D laser scanning technology (3DLST), and collaborative product life-cycle management (CPLM) can reduce fleet maintenance costs.

Housel et al. (2016) performed a cost and performance benefits comparison of insourcing and outsourcing 3DLST and 3DP for fleet upkeeping and modernization. They used risk analysis and real options valuation techniques to estimate ROI and the risk-value of various strategic real options (Housel et al., 2016). They also used Monte Carlo risk simulation to create artificial future outcomes and to analyze their characteristics accordingly (Housel et al., 2016). Based on the results of these in-depth analyses, the phased implementation approach yields the highest strategic value of the four make/buy strategies defined in this make-or-buy research (Housel et al., 2016). They recommended that the U.S. Navy adopt the three technologies investigated, test insourcing with these technologies starting with low-volume complex products, plan to increase the scale of insourcing after developing processes and a track record to justify expansion, and work to change acquisition regulations and procedures that impede the use of insourcing for parts manufacturing (Housel et al., 2016).

In the make-or-buy research, cost savings was the main driver in all contracts investigated for government insourcing initiatives from 2010 and 2011. While the course of insourcing makes business sense under certain conditions and warrants serious consideration at the fleet maintenance level, for the purpose of this research paper and the three-ship DDG 1000 program, a mix of a government and private approach, or a purely performance-based approach (outsourcing) seems to be more appropriate. The DDG 1000 program office is currently pursuing the performance-based approach for logistics support and has named it its Life-Cycle Sustainment Plan (PEO Ships, 2016). DDG 1000 does need to look at some existing organic AM capabilities as part of its risk mitigation research; however, utilizing a 100% insourcing strategy does not adhere to the fundamental government policies for competition and commercialization. Again, as discussed previously, insourcing could potentially impact the defense industry in the areas of innovation, competition, and creativity.

The FAR clearly spells out the procurement requirement in acquisitioning of commercial items, meeting socioeconomic goals, and protecting the U.S. industry base. Per

FAR 1.102—Statement of Guiding Principles for the Federal Acquisition System, the Federal Acquisition System is to

> deliver the best value product or service to the customer by maximizing the use of commercial products and services, using contractors with successful past performance, and promoting competition on a timely basis, while maintaining the public's trust and fulfilling public policy objectives.

Unlike the private companies that are mainly motivated by profits through the control of their costs, government acquisition activities are more outcome-oriented; therefore, government activities are not necessarily making business sense but making policy sense. As a result, the government may pay a premium to maintain a viable industry base and award contracts to small businesses that have high price proposals.

In the August 2014 *Guidelines For Creating and Maintaining a Competitive Environment for Supplies and Services in the Department of Defense*, DOD leadership stressed that competition is the key to motivate contractors to reduce costs and improve performance (OUSD[AT&L], 2014). A 2011 RAND report, *A Methodology for Implementing the Department of Defense's Current Insourcing Policy*, also found that the government policy for insourcing and outsourcing has historically reflected the incumbent administration's political agenda and preference (Riposo, Blickstein, Young, McGovern, & McInnis, 2011). There has been a consistent trend of the DOD outsourcing many government functions for the sake of efficiency and effectiveness (Riposo et al., 2011). The DOD expanded its use of the private sector during the 1990s and only recently reversed this trend during the Obama administration (Riposo et al., 2011). Housel et al. (2016) also mentioned the uncertain future of government insourcing in their research. In April 2009, the secretary of defense (SECDEF) announced his intent to reduce the department's reliance on contractors through insourcing. Shortly after his announcement, the SECDEF implemented a FY2011 billet freeze and halted DOD insourcing plans because of a lack of cost savings (Housel et al., 2016).

While the debate on the make-or-buy decision continues and both sides manage to present their cases, Riposo et al.'s (2011) RAND report found that it is easier to outsource than to insource. Outsourcing is more appealing in today's complex environment because of its ease and speed compared to insourcing efforts associated with working within civilservice laws and bureaucratic steps (Riposo et al., 2011). Riposo et al. (2011) concluded that the sourcing policy will continue to shift back and forth because the current laws and policies are quite vague, subject to interpretations and political preferences.

c. Maintaining the Defense Industrial Base through Competition

In the research of *Competition and Bidding Data as an Indicator of the Health of the U.S. Defense Industrial Base*, Sanders, Ellman, and Cohen (2015) looked at the competition rate among Major Contracting Commands (MCCs) and concluded that effective competition rates were falling and that this could impact the overall quality and price of products/services. Sanders et al. (2015) explained that the major discrepancies in rates of effective competition are at the MCC level, or even further down at the contracting office level. By researching several high-profile acquisition programs, Sanders et al. (2015) found that the type of system being developed influences whether, and how much, a second competitor achieves a cost savings for the DOD. Sanders et al. (2015) concluded that competition can help to control cost only when the government can clearly articulate the requirement and understand the capabilities of the marketplace. Furthermore, in separate research, Friar (2012) noted that competition will not work if the government is in a sole source environment. Sanders et al. (2015) agreed with an idea from a 2009 RAND report, which found that "second producers of electronics have been more likely to achieve production cost savings than second producers of ships and missiles" (Arena & Birkler, 2009, p. 15). This RAND report also found that the prerequisites for competition are low non-recurring costs, minimal requirements for cost improvement, sufficient demand with a large quantity, and a 50–50 chance of achieving savings (Arena & Birkler, 2009). The advent of AM can and will change this dilemma in the near future since there are potentially multiple sources that could provide solutions and service to the DDG 1000 program.

The DOD's major system acquisitions of products and services are high tech and defense-specific in nature; therefore, there is often only one qualified provider/supplier available. Moreover, competition also has transaction costs. Research shows that a contracting officer is less likely to spend additional effort to find a second supplier if he or she already has one reliable supplier. Besides, there are too many administrative burdens and it is too labor-intensive to meet the regulatory requirements, which are to develop transparent and fair competitive criteria, to evaluate the qualifications of any additional producer, and to avoid potential bid protests. Lastly, the program office has to focus on the ongoing operations and cannot quantify the benefits of competition perhaps until years later (Arena & Birkler, 2009).

Sanders et al. (2015) also showed that the services that the DOD buys represent a wide range of deliverables—from lawn care that can be effectively sourced from the commercial market to science, engineering, and technical advising services that often require defense domain–specific expertise. Due to many limitations and constraints, the government tends to rely on the original weapon system developers for long periods of time despite the fact that the government prefers competition. In some cases, there was only one developer available because of the extraordinary design requirements. In other cases, the government down-selected to one winner and could not afford a second supplier, which would require the government to acquire full technical data rights, by using the dual-sourcing approach.

As discussed previously in the make-or-buy research of Housel et al. (2016), when substantial savings could be realized as suggested, some further concerns remain: the health of the defense industrial base, training and maintenance costs of the additive manufacturing machines, specialized investment (facilities and training), and IP rights. Moreover, the government cannot afford to procure all of the data rights since there are so many technology-rich systems. Lastly, many companies participating in government contracts will not release their proprietary data rights, as pointed out in Paben and Stephens' (2015) data rights research.

Lastly, the federal government should leverage the industrial capability and resources as much as possible. General Electric (GE) has already invested around $1.5 billion over the last six years in 3D printing technology, and its planned acquisition of Germany's SLM Solutions Group and Sweden's Arcam would only bolster GE's position in the AM business (Vincent, 2016). At an estimated combined cost of $1.4 billion, GE is expanding its AM efforts and evolving into a digital industrial company (Vincent, 2016). Both companies will end up under GE Aviation, with both facilities from Arcam and SLM retaining their own management and employees (Vincent, 2016). There are few reasons for the government to acquire and manage AM companies, especially when government bureaucracy cannot adequately respond to the rapidly evolving, complex business environment.

d. Obsolescence Management Issue

Obsolescence management is not as simple as identifying which component of a weapon system will reach the end of its useful life and providing a supply community with advance notification for procurement. It is also not as simple as conducting reverse engineering and making sure the government has the organic capability for in-house work. Even if obsolescence management is outsourced to a contractor under PBL, the chosen contractor still faces the same issues and must make decisions on behalf of the government.

In the In-Service Engineering (ISE) Advisory No. 002-14 issued by Naval Surface Warfare Center, Carderock Division–Ship Systems Engineering Station (NSWCCD-SSES; 2014), the legacy Parasense refrigerant monitors, model 3340FSV-N and model 3308FSC-N, were determined to be no longer repairable due to obsolete subassemblies. NSWCCD-SSES (2014) explained that ships requiring a Parasense monitor will need to upgrade to the newer model 3300RM2. This obsolescence case has a broad impact on the fleet's operation since most Navy surface ships and Virginia-class submarines use this Parasense refrigerant monitor to detect the leakage of refrigerant within their machinery, piping, and bottle stowage areas, making sure their sailors can safely operate onboard the ships (NSWCCD-SSES, 2014). The Parasense refrigerant monitor is a commercial-off-the-shelf (COTS) item and meets the shipboard operating environment requirement, including shock, vibration, and electromagnetic interference (NSWCCD-SSES, 2014).

The government organic repair facility could not fix these legacy Parasense monitors primarily because the network module subassembly (part number 9005/3300-8) and the door module subassembly (part number 9010/3300-8) are obsolete (NSWCCD-SSES, 2014). Failure of the network module subassembly could render the network monitor out of commission (OOC). As a result, a temporary solution was to operate all supply and exhaust fans of the affected space continuously at the highest speed and implement a two-person rule when entering the affected area (NSWCCD-SSES, 2014). Ship personnel were instructed to perform Plan Maintenance System (PMS) daily with the use of portable halocarbon analyzers to monitor the affected areas (NSWCCD-SSES, 2014). Deployed ships were instructed to submit a Casualty Report (CASREP) and order the new model under Navy Item Control Number (NICN) 0099-LL-H99-1208 (NSWCCD-SSES, 2014). Ships were told to email sales@Parasense.com directly and request a pre-configured monitor (NSWCCD-SSES, 2014).

There were several issues here that dated back to 2012. First, pre-deployed ships did not have the same priority in ordering the new monitors as deployed ships. Ships that underwent shipyard availability had the lowest priority and had difficulties getting the monitors for their upcoming sea trials (certification processes for seaworthiness). It was a challenge to identify and determine which ship had priority in getting the monitors. Second, a phone call from the supply officer of DDG 58 to Parasense Inc. only served to inform that these new monitors, per contract terms and conditions, were not scheduled for delivery to the Navy stock system until the following year. Apparently, ordering the part under an NICN would not meet some ships' schedules and requirements. Third, Parasense Inc. is a privately owned small business provider of engineering and technical services, so not only is the Parasense monitor contract a sole-source contract but it also is awarded to a small company. Small businesses can go out of business for a variety of reasons. Lastly, ships do not necessarily have the necessary manpower to perform the extra PMS (some ships are manned at an 80% level). A sailor pulled from one mission area to perform the PMS could affect two different mission areas, or multiple tasking requirements, especially for ships that have small crew sizes and that depend on highly automated equipment.

It is quite clear that even with government teams for obsolescence management, engineering advisories to mitigate risks, organic capabilities for repairing, and a procurement contract with a commercial supplier in place, the Parasense monitor case still faced challenges and complexity in providing adequate foresight, procurement planning, and strategy to mitigate known and unknown risks. Although a PBL arrangement can transfer the risk of managing O&S to a contractor to a certain degree and although insourcing can provide some assurance, PBL and insourcing could still fail.

5. Current State of Technologies in Commercial and Defense Industrial Applications

AM is a more mature technology in 2016 that it has ever been and is expanding its presence across many industries and domains. In the first six months of 2016, AM has experienced rapid growth in commercial and defense industrial applications.

a. AM and Commercial Aviation

As mentioned in section B of this chapter, GE Aviation is expanding its AM and transforming into a digital manufacturing company. In the GE reports published in early 2016, CFM International, a joint venture of GE Aviation and France's Snecma, achieved a milestone in AM application by delivering the first two LEAP-1A commercial engines to Airbus on April 2, 2016 (Kellner, 2016). The LEAP engine contains 3D-printed fuel nozzles (see Figure 2) that utilize an AM technique called ceramic matrix composites, which can form parts with superalloy and ceramic material for the Airbus' A320neo passenger jet that traditional techniques cannot produce (Kellner, 2016). GE claimed that the LEAP engine is 15% more fuel efficient and has lower carbon emissions with the new AM parts, which provide more savings to airlines. As of April 2016, there are 10,400 LEAP engines on order for a total value of over $145 billion (Kellner, 2016). It is important to note that private companies are profit-driven and are thus open to AM because of the way it benefits their bottom lines.

Figure 2. LEAP: The First Jet Engine with 3D-Printed Fuel Nozzles.
Source: Kellner (2016).

GE is now leading the world in AM technology. Each of the new CFM LEAP engines has 19 3D-printed fuel nozzles that could not be manufactured through normal subtractive means. The following are some, though not all, of the benefits of printing these parts versus using conventional manufacturing: the nozzles are 25% lighter than their non-AM parts, fewer parts are needed to make the nozzle (reduced from 18 to 1), and the nozzles are more durable (Benedict, 2016). Figure 3 shows a LEAP engine in flight.

Figure 3. First Flight of a LEAP-Powered Airbus A320neo.
Source: Kellner (2016).

Besides the LEAP engine production initiative, GE Aviation is also using the AM technology on its Advanced Turboprop Engine (ATP), which eliminates 845 parts as a result (Trautvetter, 2016). The ATP will have no structural castings and have a significant weight benefit (Trautvetter, 2016). From a manufacturing standpoint, the use of AM eliminates thousands of machining requirements, inspections, and procurement contracts for engine production (Trautvetter, 2016). From a design perspective, GE uses only one design file to create the entire frame assembly, which would require 40 different data systems, 300 individual parts, 60 engineers, and 50 facilities with the conventional approach (Trautvetter, 2016). Moreover, GE can now manufacture and inspect using one additive machine and is able to repair it at one source. Lastly, GE Aviation has been aggressively working with the

Federal Aviation Administration (FAA) for certification and safety compliance on its 3D-printed parts (Trautvetter, 2016).

b. AM and the Commercial Automobile Industry

In the automotive sector, Mercedes-Benz now offers 3D-printed vehicle parts. Mercedes-Benz, a subsidiary of the Daimler Group, has harnessed 3D printing for on-demand spare parts and used 3D printing to manufacture more than 100,000 prototype parts for years. Mercedes-Benz is using AM as a solution for its low-volume parts and obsolete parts. Instead of maintaining production facilities with old tooling, Mercedes-Benz is able to create parts from old catalogs or model lines with 3D printing technology, which significantly minimizes storeroom space because parts can be printed on demand. Daimler also uses its Selective Laser Sintering printing process (an AM technology) to produce 30 different plastic truck components, from simple spacers and spring caps to complex control elements for its vehicles (Collie, 2016).

c. AM and the Commercial Shipping

Composite materials were approved to create structural components for use in commercial ships as early as December 11, 2014 (Job, 2015). This approval led to the development of hatch covers from fiber reinforced plastic (FRP), which will replace traditional steel ones on a bulk carrier (Job, 2015). These materials can be produced using current AM technology, are lighter, and produce no corrosion for a better seal. The deckhouse and hangar of DDG 1000 and 1001, the first two ships in this class, are constructed of composite material (ASN[RD&A], 2016b). As these materials are approved for use in ships, an increase in using AM seems viable.

d. AM and the Defense Industry

One of the primary defense contractors and the world's biggest missile maker, Raytheon, has accelerated its experiment of using 3D-printed parts after the U.S. Navy successfully tested a Trident II D5 missile with a 3D-printed part in March 2016 (Hollinger, 2016). AM could make enhancements to missiles—such as longer range, greater power and precision, and more functions—more feasible (Hollinger, 2016). For example, 3D-printed components can be hollow, which is difficult or impossible with traditional manufacturing methods that simply cut away material (Hollinger, 2016). Not only does weight reduction provide space for other systems or boost missile range, but it also opens up new possibilities for design with the ability to combine metals and form new alloys (Hollinger, 2016). MBDA, the European missile maker jointly owned by BAE Systems, Airbus, and Leonardo-Finmeccanica, will also experiment with 3D-printed parts in its missile system next year (Hollinger, 2016). These defense contractors expect to use AM on the front line to repair or replace missile parts, speed up availability, and eliminate supply risks (Hollinger, 2016). MBDA estimated that 3D printing could cut the production time of missile components by as much as three-quarters. Currently, it takes more than a year from the day the first component is received, according to Hollinger (2016), or longer if the design process is included. Raytheon is the prime contractor for DDG 1000's combat system suite, and BAE is currently the developer of DDG 1000's 155-mm Advanced Gun System (AGS).

Product testing and certification of AM has remained one of the main issues and concerns for many critics. One of the more advanced and encouraging developments is that Lockheed Martin recently teamed with Sciaky Inc., a Chicago-based AM company, to 3D print a mission-critical titanium propulsion tank of its satellite program (Grunewald, 2016). More importantly, Lockheed Martin and Sciaky tested the 3D-printed tank and verified that the tank was the same or better than the traditionally manufactured part (Grunewald, 2016).

In addition to time and money savings, Sciaky's Electron Beam Additive Manufacturing (EBAM) AM system demonstrate great versatility. This EBAM metal printing machine can manufacture parts that range from eight inches long to 19 feet long, has a maximum metal deposition rate of 20 pounds per hour, and is capable of combining two different types of metal in the same print job (Grunewald, 2016). Lockheed Martin and Sciaky can alter the material composition in the middle of the printing process (see Figure 4) and create hybrid parts that have not been possible without the use of AM (Grunewald, 2016).

Figure 4. The EBAM Metal 3D Printer at Lockheed Martin's Manufacturing Facility Located in Littleton, CO. Source: Grunewald (2016).

According to Marillyn Hewson, the CEO of Lockheed Martin,

> The result was a tank that met our customer's performance standards, with an 80 percent reduction in the amount of time needed to manufacture it, a 75 percent reduction in waste and a 55 percent reduction in cost. We're confident that innovations like these will continue to drive greater quality and reduce costs for our customers, which benefit our entire supply chain. (Grunewald, 2016, p. 4).

From a unit cost point of view, Lockheed Martin found that it may cost more for individual AM parts but the same 3D printing machine can be used repeatedly for a variety of parts, without the traditional needs for batch processing, reconfiguration, and other traditional machine setups, which provide cost savings across the spectrum in designing and manufacturing (Grunewald, 2016). Clearly, for low-volume and low-demand items, especially when mass production is not a viable option in designing spacecraft or satellites, AM not only improves the quality of the product but also dramatically reduces the cost, minimizes material waste, and shortens production time (Grunewald, 2016).

e. AM and the United States Navy

The U.S. Navy has supported AM research for more than 20 years and funded many AM projects at dozens of different locations (Housel et al., 2016). Across the DON enterprise, sailors, marines, and civilian scientists and engineers are experimenting with AM products and exploring 3D printing capabilities. From onboard the USS *Essex* (LHD 2), to the Marine Corps Air Station (MCAS) Cherry Point, to the Walter Reed National Military Medical Center in Bethesda, MD, the Navy and Marine Corps team is embracing AM for shipboard parts, aircraft repairs, and even cranial plates for wounded warriors (SECNAV, 2015). The Naval Sea System Command (NAVSEA) Naval Surface Warfare Center Dahlgren Division (NSWCDD) and the Combat Direction Systems Activity (CDSA) Dam Neck in Virginia are currently expanding the use of 3D printing across their science and engineering community. NSWCDD was the first warfare center with a metal 3D printer, and NSWCDD has employed AM to reduce development time for almost a decade. NSWCDD began to focus on solving fleet problems with AM by working with the CNO's Rapid Innovation Cell in 2013 (NSWCDD Corporate Communications Division, 2016).

The most recent and notable development is that Naval Air System Command (NAVAIR) now has a dedicated AM and Digital Thread Integrated Product Team (IPT) to coordinate and integrate its AM efforts. According to Elizabeth McMichael, team lead of the AM and Digital Thread IPT, NAVAIR is now focusing on using AM on its flight-critical parts (Alec, 2016). Although AM technology has been on the Navy's radar for two decades, certification and qualification have remained the primary issues. For example, an airplane's engine nacelle and link attachment can be 3D-printed in as little as three days, but it can take three months to certify them (Alec, 2016). The NAVAIR's goal is to shorten the certification process to weeks or even days by developing industry standards for 3D-printed parts (Alec, 2016).

The U.S. Navy has just revealed plans for a test flight with a Boeing V-22 Osprey with flight-critical, 3D-printed titanium parts made from titanium–aluminum alloy Ti-6Al-4V (Buren, 2016). NAVAIR plans to use the testing data as a showcase for the next generation of aircraft design, which will provide insights that the entire military–industrial complex can use to set up a digital infrastructure to manage all 3D printing data (Buren, 2016). In Buren's

(2016) news article, Dr. Bill Frazier, chief scientist of Air Vehicle Engineering at NAVAIR, testified that its 3D-printed aircraft parts showed no signs of fatigue and crack propagation whatsoever. Moreover, Dr. Frazier stressed the significance of AM, explaining that this new technology allows developers to define a quality processing envelope by taking all the knowledge and lessons learned and folding that into computational models that will help to ensure rapid replication and quality control. Buren's (2016) article also contained a prediction that AM applications will receive a huge boost in DOD spending because Defense Secretary Ash Carter recently revealed plans to spend $72 billion in R&D in FY2017.

6. Future Applications and Benefits of Additive Manufacturing

In the book *3D Printing in Space* (National Research Council, 2014), the authors suggested that AM offers technical opportunities for the Air Force in maintaining space superiority. They explained that AM enables open architectures for rapid prototyping and reconfigurability; allows low quantity production for better, faster, and cheaper systems; redefines qualification and certification for system fielding; and shortens R&D times for complex systems. AM also reduces system risk by using advanced modeling and simulation tools to integrate the materials, data, and process (National Research Council, 2014). With the speed, flexibility, and agility to produce needed parts, AM demonstrates great potential in material handling, system maintenance, and force protection (National Research Council, 2014).

The possibility also exists for 3D-printed circuit cards. There have been advances in the AM field to produce 3-Dimensionally Printed Circuit Devices (3DCD) that use Direct Write Technology (Kim, Yun, Lim, & Lee, 2015). Kim, et al. (2015) explained that the Direct Write Technology uses a conductive material such as silver paste to create the circuit paths, this paste has excellent conductivity and low resistance. The study was used to reverse engineer a cruise control switch that contained a printed circuit board (PCB), the traditional method of creating conductive circuits. The result of the engineering produced a 3DCD injection molded switch (see Figure 5) that contained the requisite functions to replace the current cruise control switch. The study concluded that the 3DCD technology used to replicate a printed circuit board was successful and provided a valid and conductive switch (Kim et al., 2015).

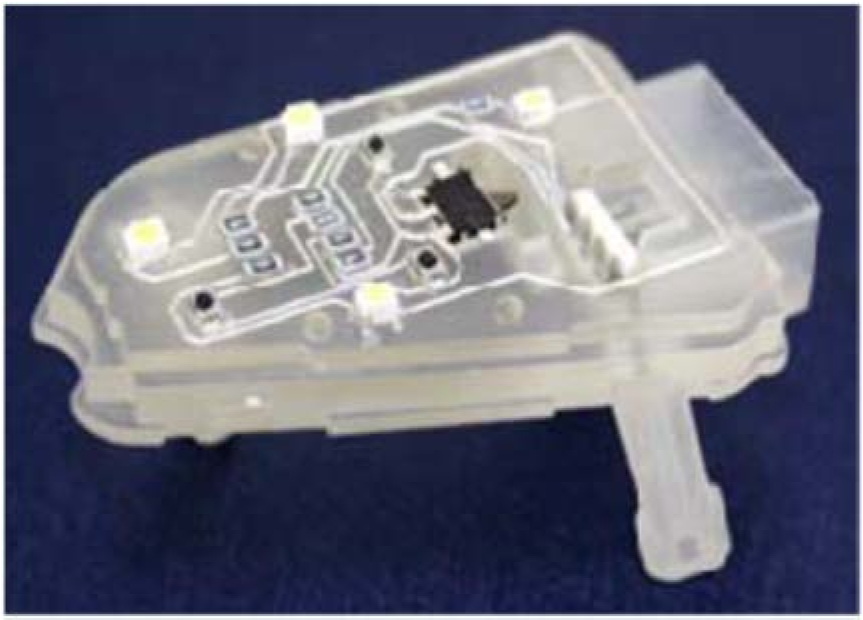


Figure 5. Fabrication of 3DCD Cruise Control Switch. Source: Kim et al. (2015).

7. Summary

AM is becoming a more recognized source of supply, and this market is advancing exponentially. Private industry has made significant strides in solving the concerns and issues around standardization, testing and certification, data rights, and so forth. It is foreseeable that AM will truly revolutionize the manufacturing industry and improve logistics support for low-volume and obsolete parts. From commercial aviation and luxury car manufacturers to major defense contractors and the DOD, financial resources are being poured into the development of AM technology. It is foreseeable that the federal government's acquisition community could take advantage of the future of increased capabilities by leveraging these innovations from both the commercial marketplace and the defense industry, as well as drawing from some organic capabilities that already exist within the government.

III. DATA AND ANALYSIS

This chapter examines the signed copy of the *DDG 1000 Zumwalt Class Destroyers Acquisition Strategy ACAT IC Milestone B Change 2*, the draft Life-Cycle Sustainment Plan (LCSP) master document, and the *Diminishing Manufacturing Sources and Material Shortages (DMSMS) Analysis of the iPDA Circuit Card* provided by the program office. Through detailed examination, this project seeks to understand what DDG 1000 currently has as its support strategy, identify gaps, and explore areas in which PBL, AM, and OSA can jointly help mitigate operation and support risks associated with a limited supplier base. This research project also compares the DDG 1000 program and DDG 51 program in terms of program size, ongoing activities, organic support, and industry support. Finally, this analysis section uses a commercial industry case of the recent arrangement among Airbus, SAP, and UPS to analyze the possibilities of a similar setup for the government to expand DDG 1000's logistics footprint with AM capabilities.

A. ANALYSIS OF DDG 1000 ACQUISITION STRATEGY

In the signed copy of DDG 1000's Milestone B Acquisition Strategy (AS) of April 26, 2016, the ASN(RD&A) approved the program requirements, program structure, acquisition and contracting approach, program risk management, design consideration, support strategy, and business strategy consideration. PBL and OSA are specifically spelled out as part of the DDG 1000 design and support considerations (ASN[RDA], 2016b). This top level, unclassified document paves the way for the introduction of AM.

DDG 1000's Technology Development Strategy clearly stated that "DDG 1000 is a technology engine for the Fleet" (ASN[RD&A], 2016b, pp. 15–16), utilizing its open architecture initiative to examine capabilities for use on future and legacy ship classes. The ASN(RD&A) determined that through the use of commercial-off-the-shelf (COTS) equipment and the requisite OSA, the ship's Total Ship Computing Environment (TSCE) can assimilate technologies as they become available. Further, the use of COTS components and open-standards based software will allow for faster modernization while minimizing costs. To maximize these benefits, the contractors will be required to provide proof that COTS or reusable non-development item (NDI) components were used wherever practicable

(ASN[RD&A], 2016b). The emphasis on integrating commercial products makes AM more relevant to the DDG 1000 program. As shown in the literature review section, both the commercial marketplace and defense industry are aggressively pursuing AM technologies, which allow rapid prototyping, fielding, and upgrading of systems.

The approved AS also provided the guidance for IP rights. The contractors will be required to demonstrate that any proprietary items required will not interfere with the OSA concept of design and upgrading systems (ASN[RD&A], 2016b). The Navy strongly encourages the use of the central, shared Navy data repository (ASN[RD&A], 2016b). This requirement will help to minimize the excessive claims of data rights, maintain OSA design, and provide data/system visibility. With this setup, the government positions itself better for negotiating data rights purchases and AM operation.

As part of DDG 1000's current Integrated Logistics Support strategy, the program office uses a mixture of organic Navy infrastructure and industry support through a PBL approach (ASN[RD&A], 2016b). An ASN(RD&A) memo dated January 27, 2007, concluded that the PBL approach to support this program is most viable (ASN[RD&A], 2016b). The DDG 1000 Program Office (PMS 500) intends to expand the potential scope of PBL support beyond traditional material support contracts and to optimize supportability across all elements of logistics (ASN[RD&A], 2016b). As shown in the literature review section, a properly structured PBL, adherent to the 10 PBL tenets, will enable reliability and availability at a reduced cost while encouraging innovation through a rewards-based system (ASD[L&MR], 2016).

Moreover, DDG 1000 used a Cost Plus Award Fee (CPAF) contract with additional performance incentives as the contracting approach for the detail design effort (ASN[RDA], 2016b). The program office stated that award fee provisions are to incentivize timely performance, cost control, and quality of the design. With a cost reimbursement type of contract, the contracting officer can use the Cost Efficiency Factor per DFARS 215.404-71-5 to motivate desired behaviors and encourage contractors to reduce costs by using innovative AM technology. The Navy also plans to conduct a full and open competition for Post-Delivery Execution Yard industrial activities of DDG 1000 and DDG 1001, which traditionally requires four conditions: minimal non-recurring costs, low-cost improvement, achievement of an economy of scale, and at least a 50–50 chance of achieving savings (Arena & Birkler, 2009). AM can eliminate the requirement for a large number of units and can satisfy requirements for non-recurring costs, cost improvement, and cost savings.

PMS 500's industrial base studies showed that Bath Iron Works (BIW) and Huntington Ingalls Industries, Inc. (HII) remain the only two shipyards capable of producing the DDG 1000 class (ASN[RD&A], 2016b). ASN recognized that BIW and HII have acquired the extensive facilities and required knowledge, based on their production of DDG-51 class ships, to be the primary shipyards to construct these state-of-the-art warships. HII's composite facilities made the shipyard instrumental in the production of the composite deckhouse and hangar. However, this report determined that actual costs incurred to date call into question whether composite materials will be a viable option in future ship construction (ASN[RD&A], 2016b). While this research is primarily focused on the use of AM to mitigate the risks of limited suppliers, AM can also lessen or remove many of those capital-intensive requirements, such as having special tools and test equipment, potentially making the construction of composite structures affordable again in the near future.

In short, the DDG 1000 program meets many of the characteristics of complex government acquisition: unique and undefined requirement, limited suppliers, rapid evolving technologies, and lack of an economy of scale. DDG 1000's AS has set the stage for implementing AM with the PBL and OSA infrastructure in place.

B. ANALYSIS OF THE DDG 1000 LIFE-CYCLE SUSTAINMENT PLAN

In the draft Life-Cycle Sustainment Plan (LCSP), dated July 31, 2016, PMS 500 identified that technical data fortifies life-cycle sustainment planning while enhancing full and open competition for sustainment and future upgrades (PEO Ships, 2016). For potential technical data needs that have not yet been established, PMS 500 included the clause DFARS 252.227-7027—Deferred Ordering of Technical Data or Computer Software—in both prime contracts (PEO Ships, 2016). When needs are identified, the technical data can be ordered for three years upon acceptance, according to this clause (PEO Ships, 2016). Since DDG 1000 is an evolutionary, technically complex ship and the Navy cannot identify all of the data requirements upfront, this 7027 clause provides some flexibility for AM initiative. The Navy can also negotiate a clause to cover the usage of AM and require the prime contractor of the

PBL contract to arrange with its subcontractor for obsolescence. The agreement should provide that upon proper notification, when the subcontractor has failed to perform or produce, the prime contractor has the right to use the subcontractor's technology and data to fulfill the PBL requirement. While some might argue that the 7027 clause alone is sufficient, due to production capacity, product life cycle, and other unforeseeable conditions, the Navy can still experience delays with the prime contractor. AM can reverse these conditions as long as the data are available and the parts are 3D-printable.

The LCSP indicated that off-ship maintenance will be accomplished through a conglomeration of the PBL contract, other maintenance support contracts, and the legacy Navy maintenance infrastructure (PEO Ships, 2016). Cost and capability are the primary concerns. The introduction of the new technologies for DDG 1000 has necessitated the creation of new support systems and infrastructure. The fiscally prudent course of action is to cluster these new services together and homeport all three ships as a group in order to promote efficiencies and maximize utilization of these services at the lowest total cost (PEO Ships, 2016). As shown in Table 4, DDG 1000 projected a $100.6 million budget reduction in O&S between FY2016 and FY2020.

Table 4. Projected O&S Cut of Zumwalt's FY2016–FY2020.
Source: PEO Ships (2016).

Fiscal Year	FY16	FY17	FY18	FY19	FY20	FY16-FY20
Delta ($ in million)	(70.0)	(52.6)	(19.9)	(12.3)	54.1	(100.6)

The Regional Maintenance Center (RMC) and its contractors can take advantage of AM and effectively lower the cost for supporting DDG 1000 and potentially expanding the maintenance and logistics footprint.

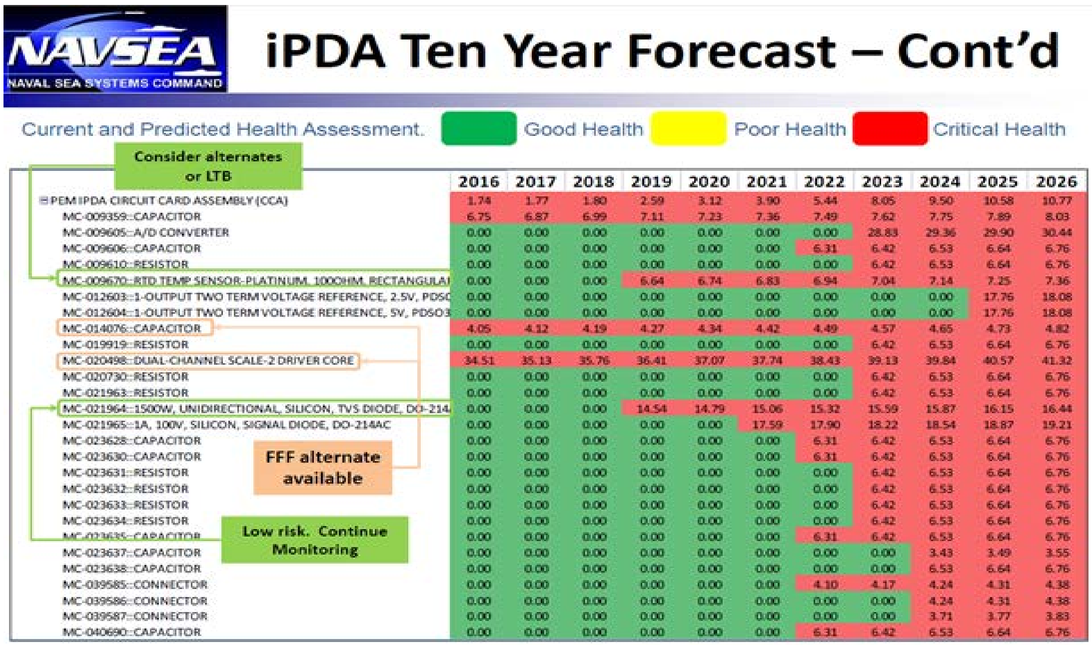
The DDG 1000 initial outfitting funds were based on historical DDG 51 class outfitting requirements with regards to "the needed on board spares, tools, test equipment, galley materials, crew support materials, medical equipment, consumables, Damage Control (DC) equipment and materials, Anti-Terrorism/Force Protection (AT/FP) equipment, and administrative support for the pre-commissioning (PRECOM) crew," with adjustments for DDG 1000's reduced crew size, stealth and signature maintenance requirements, standard of living upgrades, and Line Replaceable Unit (LRU) maintenance concept (PEO Ships, 2016). PEO Ships (2016) recognized that the DDG 1000 outfitting requirements were at a higher level than the DDG 51 class, but not quite as high as the LPD 17 class. Spare part totals will be based on Readiness Based Spare (RBS) modeling, which equates the system's need for onboard spares with the operational availability (Ao) of the systems (PEO Ships, 2016). With AM, PMS 500 can reduce either onboard spares or spares required from a shore-based facility. Moreover, onboard AM capabilities can reduce the spares needed for damage control (DC) equipment and materials.

C. ANALYSIS OF IMPROVED POWER DISTRIBUTION ASSEMBLY CIRCUIT CARD

The current DDG 1000 strategy in dealing with diminishing manufacturing sources and material shortages (DMSMS) is focused on the electronics and mission system equipment. The program office recognized that the vendor base and technology refresh cycle warrant proactive management of electronics components at the piece part level. By loading the piece part information into the Obsolescence Management Information System (OMIS), hosted at NUWC Keyport, the supply community can receive advance notice of obsolescence problems and proactively pursue low-cost alternatives. The DDG 1000 program is constantly updating its DMSMS plan.

As the lead for all DDG 1000 DMSMS issues, NUWC Keyport conducted the analysis of the Improved Power Distribution Assembly (iPDA) circuit card and identified the expected end of life (EOL) for the components that are currently obsolete or approaching obsolescence through 2019 (Southard, 2016). The iPDA is critical to support the distributed power system aboard this all-electric ship. Through the use of industry standard data (from subscription services) and historical data that was compiled from Obsolescence Management Information System data, NUWC was able to forecast when a component will potentially reach EOL (Southard, 2016). The forecast identified the relative health of the system by weighing the numbers of active suppliers, part types, and substitutes (Southard, 2016). Based on the assumptions, assessment, and analysis, a color-coded system was used to indicate current and predicted system health: green for good health, yellow for poor health, and red for critical health. Table 5 is a screenshot of a portion of the data presented in the analysis. As the data shows, the DDG 1000 program will increasingly face obsolescence issues for parts that support the iPDA starting in 2022, less than six years from the publication of this report (Southard, 2016).

Table 5. DMSMS Analysis of iPDA Circuit Card Current and Predicted Parts Obsolescence through 2026. Source: Southard (2016).



	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
⊟ PEM IPDA CIRCUIT CARD ASSEMBLY (CCA)	1.74	1.77	1.80	2.59	3.12	3.90	5.44	8.05	9.50	10.58	10.77
MC-009359::CAPACITOR	6.75	6.87	6.99	7.11	7.23	7.36	7.49	7.62	7.75	7.89	8.03
MC-009605::A/D CONVERTER	0.00	0.00	0.00	0.00	0.00	0.00	0.00	28.83	29.36	29.90	30.44
MC-009606::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	6.31	6.42	6.53	6.64	6.76
MC-009610::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-009670::RTD TEMP SENSOR-PLATINUM, 100OHM, RECTANGULAI	0.00	0.00	0.00	6.64	6.74	6.83	6.94	7.04	7.14	7.25	7.36
MC-012603::1-OUTPUT TWO TERM VOLTAGE REFERENCE, 2.5V, PDSC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.76	18.08
MC-012604::1-OUTPUT TWO TERM VOLTAGE REFERENCE, 5V, PDSO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.76	18.08
MC-014076::CAPACITOR	4.05	4.12	4.19	4.27	4.34	4.42	4.49	4.57	4.65	4.73	4.82
MC-019919::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-020498::DUAL-CHANNEL SCALE-2 DRIVER CORE	34.51	35.13	35.76	36.41	37.07	37.74	38.43	39.13	39.84	40.57	41.32
MC-020730::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-021963::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-021964::1500W, UNIDIRECTIONAL, SILICON, TVS DIODE, DO-214	0.00	0.00	0.00	14.54	14.79	15.06	15.32	15.59	15.87	16.15	16.44
MC-021965::1A, 100V, SILICON, SIGNAL DIODE, DO-214AC	0.00	0.00	0.00	0.00	0.00	17.59	17.90	18.22	18.54	18.87	19.21
MC-023628::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	6.31	6.42	6.53	6.64	6.76
MC-023630::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	6.31	6.42	6.53	6.64	6.76
MC-023631::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-023632::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-023633::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-023634::RESISTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.42	6.53	6.64	6.76
MC-023635::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	6.31	6.42	6.53	6.64	6.76
MC-023637::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.43	3.49	3.55
MC-023638::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.53	6.64	6.76
MC-039585::CONNECTOR	0.00	0.00	0.00	0.00	0.00	0.00	4.10	4.17	4.24	4.31	4.38
MC-039586::CONNECTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.24	4.31	4.38
MC-039587::CONNECTOR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.71	3.77	3.83
MC-040690::CAPACITOR	0.00	0.00	0.00	0.00	0.00	0.00	6.31	6.42	6.53	6.64	6.76

Based on the analysis, NUWC recommended that DDG 1000 establish a repair depot and Gold Disk candidates (2M repairable) and presented three options for mitigating the projected shortages:

- Option 1: Conduct Life of Type Buy (LTB) sufficient for production and sustainment for all components obsolete or predicted to be obsolete in the next 4 years
- Option 2 (Recommended): Conduct LTB sufficient for production and sustainment of DC-DC Power Supply (PS) Module and qualify FFF alternates for remaining current and predicted obsolete components
- Option 3: Conduct Life of Need (LON) buy for DC-DC PS Module sufficient for production and redesign effort and contract DRS to redesign iPDA (Southard, 2016)

While all three options can address the short-term requirement through either an LTB or LON approach, the current development, growth, and implementation of AM technology throughout the marketplace and defense industries can help to introduce a fourth option. This option could eliminate the requirement to perform lifetime buys and be in step with DDG 1000's technology development. Most of the parts cited in the iPDA analysis, such as the silicon signal diode TO-236AB, part number (PN) BAT54LT1, $0.06 each; 14-PIN TSSOP Tube, PN: AD8674ARU, $6.67 each; capacitor, PN: T495X106K050ZTE300, $2.36 each; and Platinum Surface Mount, PN: PTS080501100RP100, $1.89 each, can be 3D-printed with current technology, meeting and exceeding the current manufacturing standard (Southard, 2016). The DDG 1000 program office can easily fund and procure many of those items in large quantities because the individual unit cost is very low; however, the costs of warehousing, inventory, and tracking can add up quickly. Moreover, there are administrative costs associated with market research, procurement planning, contracting action, and program management.

One of the iPDA components, a DC-DC Power Supply Module, has no alternative part available and is currently obsolete (Southard, 2016). NUWC market research identified that a quantity of 500 is available on the open market and subsequently recommended a lifetime buy based on obsolescence analysis (Southard, 2016). However, the DMSMS analysis is limited to a five-year useful life forecast and is based on the assumption that the system will undergo an upgrade. This triggers a concern about part availability if the system is needed for more than the currently projected period. A quantity of 500 may or may not satisfy the program requirement. This DC-DC PS Module can affect the iPDA's functionality and interrupt a ship's power supply.

In a make-or-buy decision scenario, Housel et al. (2016) pointed out that high-, medium-, or low-complexity parts differ in their costs and market comparable values. However, this project for DDG 1000 concluded that the parts' contribution to fleet readiness is mainly dependent on their availability and their impact on the overall system. A low-complexity part, such as the door hinge pin of a watertight door, can prevent a ship from getting underway due to safety concerns and can subsequently affect a ship's primary mission. The availability of a small diode needed for a circuit card can effectively degrade DDG 1000's primary or secondary mission.

More importantly, NUWC Keyport has already adapted AM and created replacement parts to support the fleet (Cullom, 2014). AM was used by NUWC to create a circuit card clip for J-6000 Tactical Support System Servers installed in the submarine fleet; while this is not a technically complex part, there is a precedence for the use of AM on mission systems (Cullom, 2014). Therefore, AM warrants serious consideration in addressing the DMSMS of the iPDA circuit card issue that DDG 1000 currently has.

Lastly, as previously discussed in the literature review section, a 3D-printed circuit card assembly should be possible in the near future. Conductive material is already being tested in small applications, which could lead to greater acceptance into larger circuits.

Table 6 provides the comparison of lifetime buys and AM approaches.

Table 6. Comparison of Lifetime Buys and AM

Advantages of Lifetime Buys	**Advantages of AM**
Minimize material shortfall	Minimize production line and batch setup cost
Existing manufacturing process and setup	Eliminate dependence on production capacity
Existing industry standardization and certification	Just-in-time manufacturing
Established quality assurance procedure	Facilitate rapid prototyping and redesign
Economic of scale for large quantity orders	Satisfy low demand and low quantity order
Traditional contract negotiation or purchase order	Eliminate warehouse/inventory requirement
	Minimize transportation cost
	Increase mission readiness
	Avoid waste and reduce scrap
	Minimize interaction between human and machine

D. A COMPARISON OF DDG 51 AND DDG 1000

The DDG 51 class destroyer is currently the jewel of the surface fleet. Since its first commissioning on July 4, 1991, the DDG 51 class has demonstrated its capability to adapt new technologies, expand mission profiles, and maintain operational readiness. To date, the Navy has procured a total of 74 DDG 51 class destroyers (O'Rourke, 2016). Lewis' (2015) research showed that the DDG 51 class' OSA design allows the program to minimize duplication of technology development and share life-cycle costs among other naval shipbuilding programs. OSA is also currently the design approach of DDG 1000.

In a May 7, 2008, letter from then CNO Admiral Roughead to Senator Kennedy (as cited in O'Rourke, 2008) found that explained that the manpower savings on DDG 1000 was offset by the increase in system O&S. The CNO used a cost comparison table to discuss the operating, maintenance, and manpower costs between a DDG 51–class ship and a DDG 1000–class ship (shown in Table 7). While DDG 1000 requires a small crew size, it needs highly automated equipment to share the workload (O'Rourke, 2008). Unless DDG 1000 could find ways to lower the O&S cost, the total O&S would increase as the number of ships authorized decreased.

Table 7. O&S Cost Comparison between DDG 1000 and DDG 51.
Source: O'Rourke, (2008).

(FY$M)	**DDG 1000**	**DDG 51**
Operating (steaming)	$18.5	$15.7
Maintenance	$10.3	$5.6
Manpower	$8.5	$19.9
Total	$37.3	$41.2
Crew Size	[Total 120] 14 officers 106 enlisted	[Total 296] 24 Officers 272 Enlisted

Source: Letter dated May 7, 2008, from Admiral G. Roughead to the Honorable Edward M. Kennedy, p. 2. The figures shown in brackets for total crew size were added to the table by CRS.

The decision to only produce three DDG 1000 class ships and to restart DDG 51 production clearly showed that the Navy had shifted its focus from the DDG 1000 close-to-shore precision and volume fire support mission to the Ballistic Missile Defense (BMD) mission (Blickstein et al., 2011). Moreover, this decision increased the cost per ship construction for the DDG 1000 program, and negatively impacted DDG 1000's O&S structure. DDG 1000 shows less favorably than before in terms of meeting the mission requirement for the BMD environment and controlling its O&S cost. Consequently, DDG 51 and DDG 1000 are in direct competition for limited defense funding. DDG 51, on the surface, has advantages over DDG 1000 because of its BMD capability and its O&S cost.

While DDG 51 and DDG 1000 are in a sort of competition, many parts and systems that DDG 51 incorporates from DDG 1000 can help to increase the demand and potentially reduce some O&S risks associated with a limited supplier base. For example, the newer DDG 51 will incorporate the newly designed electric plant of DDG 1000 (GAO, 2014). As a result, both destroyer classes' electric plants will generate the sufficient quantities of needed parts, circuit cards, and subsystems for O&S. Collectively, the Navy can have a better economy of scale for 70+ ships compared to three DDG 1000s alone. Arena and Birkler (2009) explained that sufficient demand quantity was one of the preconditions for competition. While competition is a concern, sole-source suppliers also require sufficient demand quantity to justify producing parts.

Still, DDG 1000 is very different from DDG 51, with many class-specific items. For a simple illustration, DDG 1000 is roughly 63% larger than DDG 51 (O'Rourke, 2016). The iPDA analysis shown in the previous section only touches on the expansive systems. The newer design of the DDG 51–class Flight III ships will also have Air and Missile Defense Radar (AMDR); therefore, the different radar installed on DDG 1000 does not allow other classes of ships to help with the demand. Moreover, while the DDG 51–class ships might benefit from the use of cannibalization, a common practice in the aviation community, as a means to mitigate some of the O&S risks for continuous operation, DDG 1000–class ships will not realize the same advantage with systems that are only outfitted to three ships. DDG 1000 will continue to face many issues associated with its low-volume and infrequent-demand profile.

In O'Rourke's (2016) report to Congress, the financial health of shipbuilding suppliers caused concern because many of them are the sole sources for key ship components. DDG 51 and DDG 1000 both face the same issue here since this is not class-specific, but rather an industry structure–related dilemma. For example, the DDG 1000's 4160 volt electric cable, watertight doors, and propeller have only one supplier in the marketplace. The Zumwalt's iPDA already has a power supply that is obsolete, which affects the entire ship's power. It will be very difficult for the Navy to introduce a second supplier without incurring additional costs. OSA and PBL alone are not sufficient to mitigate the risk of a limited supplier base.

E. CASE STUDY OF THE AIRBUS ARRANGEMENT WITH SAP AND UPS

While Paben and Stephens' (2016) IP data rights research is less than a year old as of publication of this report, the European aviation giant Airbus has already presented a solution to mitigate and address many of the issues presented in that research. Airbus, through one of its subsidiaries, APWorks, is teaming up with SAP and UPS to solve the logistic support issues as well as mitigate the risks associated with data rights breaches and data integrity. According to their arrangement, SAP will securely deliver the data to a network of 60 UPS 3D-printing facilities, and UPS will print and certify the part for Airbus (Molitch-Hou, 2016). This joint, innovative approach provides the framework for how to take care of the data rights, data integrity, capital investment, distribution network, testing and evaluation, and certification requirement.

First and foremost, this arrangement takes advantage of SAP's supply chain management software and mitigates many IP concerns. APWorks and UPS can now connect to their vendors and securely 3D-print needed parts much closer to their customers. According to their arrangement, Airbus and its subsidiary work with SAP on the digitizing, approving, validating, and certifying of AM parts at one of the UPS locations (Molitch-Hou, 2016). This arrangement allows Airbus' suppliers to deliver their data through a secured network without surrendering their IP rights to Airbus. Airbus also eliminates the need to acquire or manage its suppliers' data and achieves cost savings.

The Navy has been working with SAP for its Navy Enterprise Resource Management System (ERP) since 2008 (Office of the Director, Operational Test and Evaluation

[DOT&E], 2014). This partnership is based on the Navy use of the ERP application architecture to support the business enterprise by providing supply chain visibility, funds accountability, and personnel hours, among other applications (DOT&E, 2014). The Navy should use this arrangement to engage SAP and request information in similar AM data management services provided to Airbus.

Second, this arrangement among Airbus, SAP, and UPS is an example of how Airbus and APWorks have expanded their logistics footprint by leveraging UPS' AM capabilities and resources. Airbus might have the resources to put 60 AM facilities in the United States; however, there is no need for it. UPS already has the AM machines and capabilities to satisfy Airbus' requirement. Similarly, there is no need for the government to invest in AM manufacturing facilities and upkeep of the AM machines if the commercial marketplace can adequately satisfy the government's requirement. Raytheon, Lockheed Martin, BAE, General Electric, and Boeing are the major defense contractors that have already demonstrated their AM capabilities. Specifically, Raytheon is the prime contractor for DDG 1000's combat system suite, and BAE is the developer for DDG 1000's 155-mm Advanced Gun System (AGS). Raytheon and BAE should consider AM as part of their product support strategy for DDG 1000.

Third, as Airbus and APWorks leverage UPS' capability to operate a 3D printing service network, Airbus and APWorks can connect 3D printing experts with end users (Molitch-Hou, 2016). By doing so, the partnership provides Airbus and APWorks the ability to design or redesign parts quickly and to 3D print on demand (Molitch-Hou, 2016). In a similar arrangement, the Navy connects its suppliers with its end users, sailors, government employees, and contractors for the design and redesign effort. AM can help DDG 1000 achieve the given objective of Open Architecture and deliver a broad range of capabilities to future and legacy ship classes, as well as to other enterprise platforms. According to Molitch-Hou (2016), not only does AM provide Airbus with the ability to produce parts at the needed locations, but it leads to a better weight ratio for the aircraft. For example, an A350 aircraft could achieve a weight reduction by nearly a ton with all the possible 3D-printed components (Molitch-Hou, 2016). Weight reduction can help the Navy save on fuel costs and provide DDG 1000 with a wider growth margin in system capability.

Fourth, customers of Airbus can determine the costs of AM parts and compare them to traditional manufacturing parts by taking advantage of SAP Product Life-Cycle Costing (Molitch-Hou, 2016). For Airbus, such an arrangement not only reduces the cost, time, and carbon dioxide (CO2) emissions associated with shipping, but also allows APWorks to focus on a new distribution scheme through an on-demand 3D-printing cloud service that is used to produce on-demand aerospace components at many locations throughout the United States that meet part specifications and standards (Molitch-Hou, 2016). In order to maintain a global presence and be ready for national tasking, DDG 1000 and the Navy need an improved sustainment capability in this reduced fiscal environment. AM promises cost saving and timely delivery.

> Lastly, Torsten Welte, the global head of Aerospace and Defense for SAP, stated,
>
> Innovation in on-demand 3D printing is now revolutionizing traditional manufacturing. In the next few years, 3D printing will be widely adopted across manufacturing industries. The aerospace and defense market will transform digitally to strive to achieve near-zero unplanned downtime on commercial flights as well as support high production turnaround at a lower cost. What makes 3D printing most attractive in aerospace is the removal of many costs associated with traditional manufacturing like stocking inventory. Users are enabled to print the parts they need, as needed. (Molitch-Hou, 2016, p. 2)

Welte also predicted manufacturers will no longer face the physical constraints of centralized facilities and will be able to satisfy their customer with AM parts at distributed hubs, which will save companies thousands of dollars in shipment and warehousing (Molitch-Hou, 2016). DDG 1000's LCSP currently has clustered its services together to promote efficiencies and maximize utilization with the aim of achieving lowest total cost. AM can help to alleviate the fiscal constraint and enable the Navy to reshape its vision in parts distribution, system support, and much more. While this case study is more relevant to the aerospace industry, DDG 1000 can still take advantage of a similar arrangement and can be the shinning technology engine for the fleet.

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IV. FINDINGS AND RECOMMENDATIONS

A. FINDING 1 AND RECOMMENDATIONS

This project's first research question was: How should the government structure PBL contracts that will incentivize the use of AM? Based on the available data, it is clear that the DDG 1000 program can effectively mitigate the risks associated with a limited supplier base for key Navy ship components by taking advantage of AM with properly structured PBL arrangements.

In order to take advantage of the capabilities and potential that AM offers, the government needs to structure performance-based arrangements that will help to extract innovation, motivation, and collaboration from its contractors. As the 2016 update to the DOD PBL guidebook stated, "...PBL is not a one-size fits all tool…evidence provides a compelling case that performance-based sustainment is both a successful and robust strategy" (ASD[L&MR], 2016). While PBL arrangements can transfer the risk of managing O&S to a contractor to a certain degree and in-sourcing can provide some assurance, PBL and in-sourcing can still have shortfalls.

There are additional challenges for entering a PBL relationship with commercial vendors and defense contractors with the aim of taking advantage of the most revolutionary manufacturing process. First, the government has to incorporate AM as part of its requirement, acquisition strategy, and sustainment plan. Then the government needs to solicit the ideas, offers, and solutions from the marketplace and defense industry. Since the current state of technology makes AM more ideal for low-volume and low-quantity production, the government will need to use incentives to elicit desired behaviors and extract performance outcomes. It is not as simple as increasing the profit margin and reimbursing allowable costs, but entails careful planning, analyzing, monitoring, and evaluating with adequate goals, metrics, and methodologies.

The government understands its requirements well, or at least, the quantity and the delivery schedule of the requirements, while the contractors know their capabilities better. If the government does not clearly specify the requirement of incorporating AM as part of the PBL contract, the contractor will have the ambiguity and freedom to decide how to satisfy the government's needs. Since traditional manufacturing facilities are still in use and a large order quantity provides good profit, some contractors will have less incentive to introduce AM as part of a solution and will continue to expect that a large quantity was the primary means to achieving cost savings. More importantly, it is in the government's best interest to identify AM vendors through market research as soon as practical and promote competition.

While the 2016 release of the PBL guidebook provides the DOD with the 10 tenets for PBL arrangement, the strategic considerations for IP rights, the data collection phase process, and the steps for the implementation of PBL, this project looked into the FAR and DFARS, which identified two specific incentives the government can use to elicit the desired outcomes. AM requires companies to sink substantial investments, in both resources and manpower, to keep pace with the new technologies/sub-technologies that are constantly evolving in the marketplace. At the same time, existing, traditional manufacturing facilities, resources, and processes are competing for resources and remain significant for their known advantages. Therefore, it is important to use the efficiency factor during PBL contract negotiation to spur investment in innovative manufacturing processes, particularly in AM. Also, this project shows that most of the defense contractors who aggressively pursue AM are the well-established industry giants. In order to maximize small business participation in AM and extract nontraditional solutions, the government needs to use the FCCOM to assist, reimburse, and compensate the contractors' capital investment.

As the government uses significant, irresistible incentives to lead the industrial revolution in AM, the government can effectively reshape the defense industry landscape. The government can reduce its risk of a limited supplier base by having a second supplier, or multiple suppliers, for its system acquisition and service support, particularly in the low-volume, low-quantity defense articles. In short, the PBL guidebook laid the generic, strategic framework for contract support, and this project identified the actionable items for execution by evaluating the environment, requirement, and characteristics of AM. A properly structured PBL contract could help to alleviate the workload of the contracting officer by placing this requirement on the prime contractor, thus helping to improve competition and achieve cost savings. With an adequate, carefully designed, and innovative PBL approach, the government can encourage research and development AM while helping contractors to improve the quality, reliability, and performance of their products and services.

B. FINDING 2 AND RECOMMENDATIONS

This project's second research question was: If the government decides to insource, what are the considerations in make-or-buy decisions? It found that AM makes just-in-time manufacturing (JIM) for many critical components a reality and largely eliminates the need for lifetime buy, which enables the government to shift its focus from manufacturing in-house to managing the support services.

For the past eight years, there has been an increasing push towards government insourcing. Insourcing, indeed, is a way to mitigate risk and provide some assurances when the marketplace cannot satisfy government requirements. However, reliance solely on insourcing could hurt the defense industry by eliminating the need for some companies.

PBL is more of a buzzword than an attainable goal if the steps identified in the PBL guidebook and requirements from customers are not achievable or attainable. PBL is also not a one-size-fits-all tool (ASD[L&MR], 2016). The same rule applies here: insourcing is not the ultimate solution. As this project shows in its research of the obsolescence management case associated with the Parasense sensor, even with dedicated government teams for obsolescence management, engineering advisories for risk monitoring and mitigation, organic capabilities for repairing, a procurement contract and commercial supplier in place, insourcing does not address all the challenges and complexity of supporting complex defense systems. Moreover, the government does have certain limitations and constraints for ensuring that parts meet specifications. Despite the fact that the DOD has engaged AM for more than 20 years, the government has been a little behind on establishing the qualification or certification process for the use of 3D-printed parts as critical items on weapon systems. In contrast, the qualification, certification, and standardization of AM parts to meet FAA requirements and fielding for commercial use came from GE, without the direction or requirement from any government entity. NAVAIR's recent effort to shorten the AM parts certification process to weeks or even days by developing industry standards for 3D-printed parts is probably the area in which the government can most effectively add value to its operation and make sure it has access to this required capability.

As a result, the government's main challenge is to find the right balance between its essential need for insourcing and the many benefits and capabilities AM capabilities offer.

To do so, the government needs to evaluate its capacities and mission profiles carefully. First and foremost, the government is not in the manufacturing business and should focus on the inherent government functions that cannot be contracted out. In the operation and support of defense weapon systems, many parts and services are considered to be mission critical; however, producing these parts and providing the maintenance and services for them are not inherently government functions. Secondly, parts and services can definitely lead to a life-or-death issue, especially on the battlefield or in contingency situations. However, it is more important that the government can manage and satisfy its requirements through the proper sourcing strategies and channels, instead of providing the services or materials in-house.

To be more specific, perhaps the government needs to find ways to manage the IP rights for the use of AM and provide the regulatory oversight on the standardization, qualification, and certification of AM parts. Instead of relying on contractors to tell the government what to buy, how to manage, and how much to pay, the government probably should focus on insourcing those inherent government functions and be able to coordinate its efforts in the use of AM. Precisely as the SECNAV stated in his memo to the CNO, CMC, and ASN(RD&A), the DON needs to increase the development and integration of AM, as well as develop the ability to qualify and certify AM parts (SECNAV, 2015). Moreover, the second half of SECNAV's 2015 memo identified standardization of the digital AM framework, end process integration, establishment of the DON advanced integrated digital manufacturing grid, and formalized access to AM education, training, and certifications for the DON workforce as more important than organic capabilities. Through the evaluation of the arrangement among Airbus, SAP, and UPS, this research project showed that Airbus is more concerned with selecting the right data management firm, SAP, and capable AM manufacturer, UPS, to satisfy the requirements for meeting its operational and logistical support demands for Airbus' global network.

C. FINDING 3 AND RECOMMENDATIONS

This project's third research question was: How can the DDG 1000 program leverage the capabilities of AM for its existing and future requirements? The research indicated that in addition to handling properly structured PBL contracts and OSA design, AM can also offer rapid design prototyping and system upgrading, making it easier to upkeep, update, and upgrade DDG 1000.

AM can improve competition and lower the risks associated with a limited supplier base by adding a second competitor, lowering the nonrecurring costs, eliminating the need for an economy order quantity, and achieving cost savings. AM could allow rapid prototyping; with an OSA design, more small businesses can research, develop, and test their products as subcontractors and help to improve the DDG 1000's capabilities, reliabilities, and sustainability. Last but not least, the use of AM will allow easier incorporation of the open architecture idea to develop new systems while using interface management.

Southard's (2016) iPDA analysis showed that the little bits and pieces of a circuit card can significantly affect the DDG 1000's mission and the obsolescence management forecast is only as good as the current data provided by the marketplace and industry for the next five years. At the same time, the obsolescence case of the Parasense sensor showed that the government sometimes needs to forecast further out into the future, perhaps 25 years or more. In the event that AM becomes the predominant manufacturing process for many low-demand, low-volume parts, the government can take advantage of this revolutionary market dynamic with proper planning. By using a properly structured approach with PBL, OSA, and AM, the government can predict, anticipate, and manage the risks of limited key ship components.

For existing requirements, the government could look into existing AM efforts among government agencies and leverage the equipment on hand from the multitude of entities that have already embraced this technology, including the Department of Energy, NASA, the USS *Essex*, Marine Corps Air Station (MCAS) Cherry Point, and Walter Reed National Military Medical Center in Bethesda, MD (SECNAV, 2015). NUWC, or a designated team, could look into the organic AM capabilities and determine if the government can 3D-print some iPDA parts. Moreover, since GE is not only the maker of the LEAP engine for commercial aviation but also the manufacturer of the LM-2500 engine for the Navy's Arleigh Burke–class destroyers, Ticonderoga-class cruisers, and America–class amphibious ships, the government should investigate the capabilities that GE has for certain existing engines' parts support and system upgrades. Last but not least, the DDG 1000 program can bring the composite deckhouse back onto the negotiation table since 3D-printed composite materials were approved for structural components of commercial ships in 2014 (Job, 2015).

For future requirements, the government should incorporate and insist on the use of new technologies to produce obsolete and low-volume/demand requirements when negotiating PBL arrangements with contractors. Since BAE is currently the prime contractor for DDG 1000's combat system suite and is also aggressively pursuing AM capabilities, it is important to have a discussion on the use of AM for system acquisition and O&S planning. BAE is also more likely to become the PBL provider based on current trends and defense industry environment the government is in; therefore, it is imperative for the government to understand and define its requirement and develop and negotiate the proper measurement metrics for program execution. For certain military requirements, such as the DDG 1000's propeller, the challenge is to meet those stringent standards under extreme conditions. For example, a 3D-printed propeller for a naval warship would need to pass the shock test and sustain a prolonged period of high-speed maneuvering. It will be worth the effort to investigate the EBAM metal 3D printer, located at Lockheed Martin's manufacturing facility, which is capable of metal-printing parts up to 19 feet long. The government should direct its effort towards AM and take advantage of the SECDEF's plan to spend $72 billion on R&D (Buren, 2016).

Similar to PBL and insourcing, AM is a revolutionary manufacturing process that has certain limitations with the current state of AM technologies. AM is also not a one-size-fits-all tool/solution and might not be cost effective for every application. For example, manufacturers will continue to use their existing facilities and resources to produce those high-volume and low complexity parts until the costs of maintaining those resources are no longer economically sound. In short, AM or 3D printing by themselves may not be the solution for many existing and future requirements; however, when the government can combine them with PBL and an open system approach, the government can significantly lower a program's cost, performance, and schedule risks. It is predictable that the Navy, especially the DDG 1000 program office, can benefit from AM development immediately and in the near future.

V. CONCLUSIONS AND AREAS FOR FURTHER STUDY

A. CONCLUSIONS

The DDG 1000 program's re-baseline, budget cuts, technology maturity issues, cost increases, and other unknown risks could have led these three ships into a perfect storm and a much cloudier, muddier future. Additionally, most of the DDG 1000 suppliers are sole-source and therefore enjoy a certain monopoly of power in the marketplace. Even though DDG 1000's increased parts costs associated with a sole-source or limited sources environment is a valid concern, the fact that DDG 1000's suppliers' mere existence can significantly affect the program's performance is the primary concern for long-term O&S planning. As this project shows, without an effective way to lower startup costs and extract ROI, the government will not obtain competition or maintain a healthy industry base. AM, a revolutionary manufacturing process, is the potential answer to these problems.

The DDG 1000's OSA and PBL, by design or by accident, have jointly crafted an environment for the introduction and implementation of AM. The DDG 1000 program does not have scale economies due to the number of ships; therefore, DDG 1000 needs to seriously consider AM as a means to satisfy its low-volume, infrequent-demand requirements, as well as to mitigate the risk of a limited supplier base. AM can help to improve material availability and alter the traditional obsolescence management approach that is more likely to result in lifetime buy decisions with possible limitations. With PBL, OSA, and AM, the program office can invite more interested parties to participate and thus mitigate the risk of losing existing contractors. Since many of the major AM developers, such as SAP, BAE, Lockheed Martin, and Raytheon, are also the primary service providers of the DON, and since the Navy has similar or better resources for DDG 1000 to mirror the agreement that Airbus, SAP, and UPS developed, AM is a viable solution in mitigating the risks identified in this research.

AM will not replace conventional manufacturing methods for high-volume, low-complexity parts in the near term and foreseeable future; however, AM will continue to evolve as the process matures and will significantly alter make-or-buy decisions low-volume, low-quantity items. DDG 1000, as the tech engine for the fleet, will reap the benefits of rapid prototyping, faster production, better quality parts, lower prices, and minimum risks that AM offers.

B. RECOMMENDATIONS FOR FURTHER STUDY

Additional research of AM could focus on the DON's ability to expand its logistic infrastructure with government organic support and PBL arrangements. Specifically, subsequent research could inventory the AM capabilities within the DOD and identify gaps and opportunities among the Navy, the Army, and other services. Subsequent research could also survey the marketplace and identify the potential AM providers for PBL consideration. The earlier the government can identify companies like UPS, whose distributed AM capabilities allow multiple locations to create parts, the better options the government will have for its decision-making.

Future research could also survey and research IPT teams across the DOD enterprise and identify whether AM is reflected in their planning, market research, solicitation, designing, and O&S planning. Through the identification of the AM awareness, education, and training requirement, the DOD could explore how its components can coordinate the development and integration of AM. Some questions to consider are: What are the changes needed to implement AM in the acquisition process? What can be included in the Better Buying Power (BBP) initiatives? Where can AM help to facilitate the implementation of BBP 3.0 or enhance the not-yet-released BBP 4.0?

Lastly, future research could explore the latest AM developments and focus more on the technology maturation, risk reduction, and manufacturing phases of DOD acquisition. Among the benefits of this research is a possible answer to the question of whether AM could lead to the future integration of the air and missile defense radar (AMDR) by making it cheaper, lighter, and smaller. Currently, the Navy removed the AMDR from DDG 1000 due to a Nunn-McCurdy breach and decided to acquire a scaled-down AMDR for DDG 51 Flight III because of the need to accommodate the size of the ship. The smaller AMDR is not quite as capable as the original design.

C. SUMMARY

Looking forward, the advent of AM and associated future technology advancements will continue to reshape the industry landscape and challenge the business decision-making process. From the commercial marketplace to the private defense industry, AM is aggressively pursued and incorporated into business decisions. The challenge for the DOD acquisition community, across the spectrum from system engineering to contracting, is to incorporate AM in decision-making throughout all phases of the product life cycle. There are many uncharted areas for the use of AM developments to identify the capability gaps, to improve system readiness, and to meet future mission requirements; therefore, the DOD must lead from the forefront and take a holistic approach to integrating AM. Defense system acquisition, like the DDG 1000 program, can significantly benefit from the use of AM and drastically reduce the risks of limited key components.

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