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Case Study of the Naval Surface Warfare Center Indian Head Additive Manufacturing Initiative

December 2023

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Prepared for the Naval Postgraduate School, Monterey, CA 93943.

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ABSTRACT

Additive manufacturing (AM) is a manufacturing paradigm revered by the United States with inspired interest, as the Department of Defense (DOD) strategizes to revitalize its industrial bases. AM is a vital component of the DOD strategic initiatives to implement an agile supply and logistics framework. The Office of Naval Research, in collaboration with the Naval Surface Warfare Center Indian Head Division, is conducting the Energetic Materials Additive Manufacturing (EMAM) study. The catalysts for the study are the high rate of anomalies and constraints of traditional manufacturing. The EMAM study objective is to determine the efficacy of two AM methodologies, Direct Ink Write and Digital Light Processing, in relation to the manufacturing of propellant. Painter suggests the long-term goal is to field the AM product upon the successful completion of design verification testing and qualification. EMAM research indicates that AM of propellant is a viable alternative to traditional manufacturing. The Direct Ink Write methodology is a feasible solution to address the Hercules Experimental Smokeless 5808 quality concerns, while fostering sustainable practices. An evaluation of the EMAM project concluded that a cost-benefit analysis, formalized processes, and protocols are necessary to establish a formalized acquisition program. The investment of resources will enable future research and development, technological advancement and warfighter readiness.



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We would also like to extend our sincerest thanks to the Naval Surface Warfare Center, Indian Head Division Energetic Materials Additive Manufacturing team, Energetics Manufacturing Technical Center director, Cartridge Actuated Device Propellant Actuated Device (CAD/PAD) Joint Program Office, and CAD/PAD Acquisition Specialists. Their input and assistance were invaluable towards the completion of the capstone applied project/thesis. Furthermore, we would like to extend a special tribute to David Palmer, Magdy Bichay, Efram Perry, Dr. Dan Minehan, and our advisor, Dr. Robert Mortlock, for their time and support throughout the process.



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LIST OF ACRONYMS AND ABBREVIATIONS

3D	Three-Dimensional
AM	Additive Manufacturing
A&S	Acquisition & Sustainment
BTI	Barriers to Implementation
CAD/PAD	Cartridge Actuated Devices/Propellant Actuated Devices
CAP	Capstone Applied Project
DIB	Defense Industrial Base
DIW	Direct Ink Write
DLP	Digital Light Processing
DOD	Department of Defense
DVT	Design Verification Test
EMAM	Energetic Material Additive Manufacturing
GAO	Government Accountability Office
HES	Hercules Experimental Smokeless
IHD	Indian Head Division
IP	Intellectual Property
JIT	Just-in-Time
JPO	Joint Program Office
MIB	Manufacturing Industrial Base
MPEG	Methyl Phthalyl Ethyl Glycolate
MRL	Manufacturing Readiness Level
MTS	Manufacturing Technology Systems
NAVAIR	Naval Air Systems Command
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
OIB	Organic Industrial Base
ONR	Office of Naval Research



OSD	Office of the Secretary of Defense
PMI	Program Management Institute
R&D	Research and Development
SWOT	Strengths, Weaknesses, Opportunities, and Threats
SCR	Supply Chain Resiliency
STL	Stereolithography
TRL	Technology Readiness Level
U.S.	United States
UV	Ultraviolet



EXECUTIVE SUMMARY

Continual research and development facilitate the advancement of additive manufacturing (AM). The Office of Naval Research and the Naval Surface Warfare Center (NSWC) Indian Head Division (IHD) Energetic Materials Additive Manufacturing (EMAM) study supports strategic objectives to strengthen the manufacturing Industrial base (MIB) and defense industrial base (DIB). Both the MIB and DIB are subsets of the Organic Industrial Base (OIB), which is the focal point of the U.S. initiatives to support self-sustainment.

The Hercules Experimental Smokeless (HES) 5808 and the adaptation of AM are the focal points of the EMAM study. HES 5808 is a critical component of the M91 Impulse Cartridge, which is utilized in the AV-8, F-5, F-16, and T-38 aircrew escape systems. The catalysts for the study are the high rate of anomalies and constraints of traditional manufacturing. The study objective is to determine the efficacy of the AM methodologies Direct Ink Write and Digital Light Processing in relation to the manufacturing of propellant. Moreover, the long-term goal is to field the AM product upon the successful completion of design verification testing and qualification (Painter, 2022). The EMAM study achievements are the material and formulation development, establishment of a manufacturing facility, corrected design anomalies, and preparation to enter the demonstration phase. The nontraditional manufacturing paradigm has the potential to address the NSWC IHD MIB risks and production issues. The incorporation of AM as a secondary source could mitigate future supply chain disruptions.

From a collective standpoint, the United States' economic nationalism efforts and OIB restorative initiatives are interdependent, as evidenced by the supply chain disruptions during heightened crises. The current geopolitical events and COVID-19 pandemic highlights the importance of self-sustainment (White House, 2021). The criticality of the supply chain shortages is an indication of the just-in-time manufacturing and supply chain strategy deficiencies.



Consequently, supply chain resiliency is the focal point of the compulsory Department of Defense strategic initiatives (White House, 2021). Nontraditional manufacturing paradigms are a vital component of the OIB restorative plans. AM is a viable paradigm that is evidenced by a notable characteristic, limitless flexibility (Eyers et al., 2018). While the term *limitless* is synonymous with *immeasurable*, the effectiveness of AM is measurable in terms of both proactive and reactive supply chain and logistics proficiency (Naghshineh & Carvalho, 2020). The intrinsic AM trait is that limitless flexibility cultivates business, environmental, and economic adaptability or sustainability. In addition, the characteristic is attributable to capability gap solutions, project management principles, and decision-making models. A culmination of agile, flexible, and sustainable manufacturing paradigms, policies, processes, and principles foster a resilient OIB.

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I. INTRODUCTION

This capstone applied project (CAP) has a multifaceted conceptual framework that explores additive manufacturing (AM) from the Organic Industrial Base (OIB) and Energetic Materials Additive Manufacturing (EMAM) perspectives. The CAP research assesses the relationship of AM and the OIB to determine the benefits, constraints, and impact to the restorative initiatives. Correspondingly, the EMAM perspective includes an exploration of the AM methodologies in relation to the manufacturing of propellant. The CAP provides an analysis of the key issues and risks associated with the defense Industrial base (DIB) and manufacturing industrial base (MIB). Both the DIB and MIB are subsets of the OIB, which are comprised of manufacturing and sustainment support facilities. Moreover, this CAP provides an examination of the contributions of the Office of Naval Research (ONR) and Naval Surface Warfare Center (NSWC) Indian Head Division (IHD) in support of Department of Defense (DOD) strategic imperatives.

Considerations for nontraditional manufacturing paradigms are imperative to restore the MIB and DIB (Office of the Secretary of Defense for Acquisition & Sustainment [OSD A&S] Industrial Policy, 2021). Furthermore, global circumstances underscore the relevance of AM technology (Mahmood et al., 2022). The advancement of resilient and agile practices warrants disruptive technologies and innovation. The distinctive AM attributes enable optimal reactive and proactive strategic planning (Naghshineh & Carvalho, 2020).

A. PROBLEM STATEMENT

According to the Office of the Secretary of Defense for Acquisition & Sustainment (OSD A&S) Industrial Policy research, the magnitude of the industrial capability gap is evidenced by the country's decline in global prominence with respect to international markets (OSD A&S Industrial Policy, 2021). Consequentially, there is a newfound sense of economic nationalism and the obligatory DOD initiatives to advance both the DIB and MIB. As China gains global dominance, strategic initiatives to foster sustainability, incentives to reshore manufacturing businesses, and strategic plans to restore the capability



gap are imperative (OSD A&S Industrial Policy, 2021). The challenge of restoring the industrial bases, in turn, is the catalyst for research and development (R&D) to advance the direct digital manufacturing paradigms—referred to in colloquial terms as AM and three-dimensional (3D) printing.

Per a Government Accountability Office (GAO) analysis, the key industrial base risks are derived from the supply, manufacturing, economic, and acquisition policies and education capability gaps (Russell, 2022), as described in Figure 1. Consequently, these root causes have underlined the national security vulnerabilities (Russell, 2022). The GAO enterprise-wide assessment validates the concerns regarding the diminishing OIB and asserts that the diminishing DIB, MIB, and U.S. competitive advantage are interrelated. While there are varying perspectives regarding the collective root cause, the GAO report indicates globalization is a primary factor. Each of the industrial base risks are indicators of a destabilized ecosystem, a subsidiary byproduct of globalization.



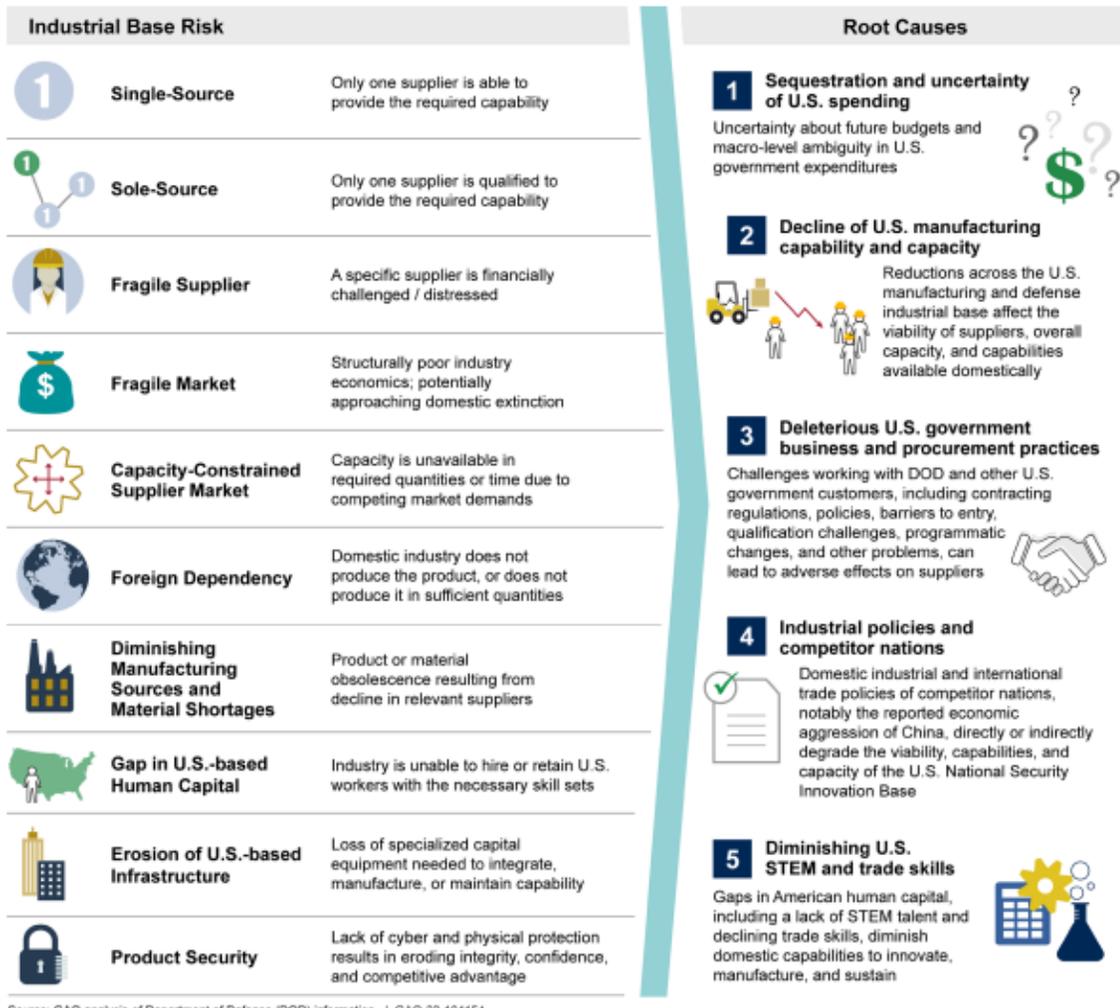


Figure 1. DOD-Identified Industrial Base Risk Types and Root Causes. Source: Russell (2022).

Foreign dependency is the foundation of the current supply chain and logistics infrastructure. The strategy does not align with the lessons learned from the recent heightened crises analysis. Self-sustainability is of the utmost importance, as proven by the current geopolitical and COVID-19 crises. By the same token, a resilient U.S. supply chain and logistics infrastructure are vital to restore the DIB and MIB. To the same degree, the identification of a risk mitigation strategy is of the essence. Risk mitigations, such as agile business and procurement practices, diversification of sources, and incentives to reconcile

the domestic supplier and education disparities are imperative to restore the industrial bases (National Defense Industrial Association [NDIA], 2023).

AM is a viable solution to support the risk mitigation of the supply chain and manufacturing capability obstacles. While there are opposing viewpoints regarding the most effective supply and logistics infrastructure, it is clear that the inclusion of nontraditional manufacturing supports the diversification of sources.

The GAO has suggested that stockpiling is a tenable solution (Russell, 2022), but this supply model precipitates issues, such as obsolescence. In contrast, the just-in-time (JIT) model lessens the risk of obsolescence; however, the model's ineffectiveness was exposed during the COVID-19 pandemic and geopolitical conflicts. While AM is supportive of a JIT supply model, the methodology has the potential to address high and low demand volatility (Alogla et al., 2023). The methodology can also address supply chain vulnerabilities through strategic positioning in that geographic and regional locations lower the risk of supply disruptions. A strategic mechanism, such as AM, can supplement the global supply chain in conjunction with a streamlined acquisition process.

In addition, supplementary AM practices lessen the capacity-constrained supplier market risk. AM facilitates the OIB restoration by reshoring the manufacturing capabilities. The continual R&D of AM promotes the expansion of materials and methodologies. A positive consequence of AM is the identification of alternate materials. As a result, these research efforts lessen the risk of diminishing sources and materials. AM projects require fewer team members and less space and, therefore, less risk associated with human capital. In terms of the erosion of the infrastructure, AM strengthens the industrial base by reshoring cost-effective manufacturing solutions. AM addresses the product security risk by reshoring the manufacturing facilities.

B. RESEARCH PURPOSE

The R&D of AM is an integral component of the DOD roadmap to restore the industrial bases. This CAP provides an evaluation of the feasibility of AM to address industrial base risks. The CAP objective is to determine the benefits and constraints from a collective and NSWC IHD perspective with respect to supporting the DOD strategy.



Furthermore, this chapter provides a succinct overview of the derivation of the sources, analysis techniques, and data collection tools.

C. METHODOLOGY

This section provides an overview of the research proposition and explicates the correlation to the research methodology approach, research design, and methodological limitations, as illustrated in Figure 2. The methodology attributes are reflective of the project objective—to cultivate the exploration of AM and the EMAM study relationship to the DIB restoration strategies. This research utilizes a case study–based research methodology to study the NSWC IHD EMAM project.

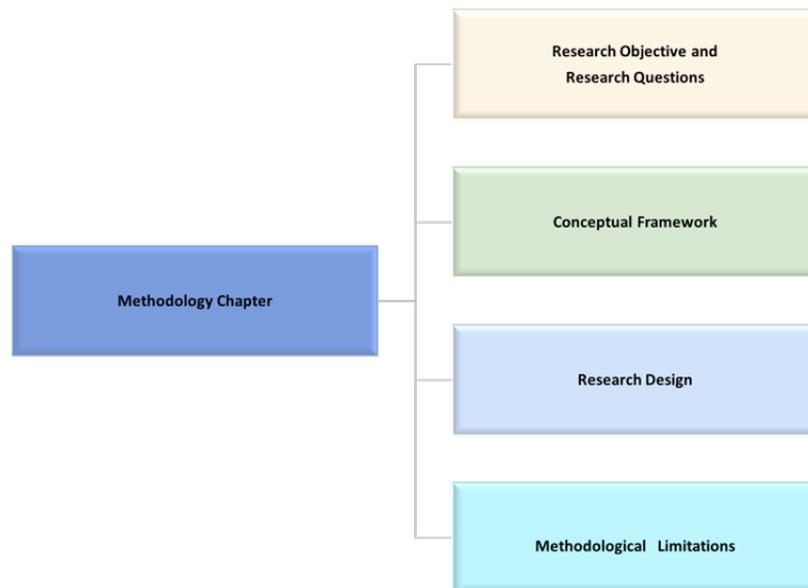


Figure 2. Methodology Chapter Structure

D. RESEARCH AIM AND QUESTIONS

Per the DOD strategy, corrective measures are required to restore the DIB and MIB capability gap. The current OIB infrastructure is reflective of the political, economic, and technological influences. As the political, economic, and technological competencies evolve, R&D is pertinent to address the DOD competitive disadvantage. The research questions are derived from the project statement and objective:



1. What is the value proposition that additive manufactured parts or systems bring to delivering warfighter capability?
2. What are the benefits of utilizing AM to support the warfighter?
3. What acquisition strategies would apply to the AM initiative?
4. What are the barriers to implementation (BTI) for AM based on this case study?

E. CONCEPTUAL FRAMEWORK

The NSWC IHD EMAM project and comprehensive conceptual framework is indicative of the multifaceted research premise. Hence, the conceptual frameworks denote the variables from the NSWC IHD project and collective viewpoints, as illustrated in Figure 3 and Figure 4.

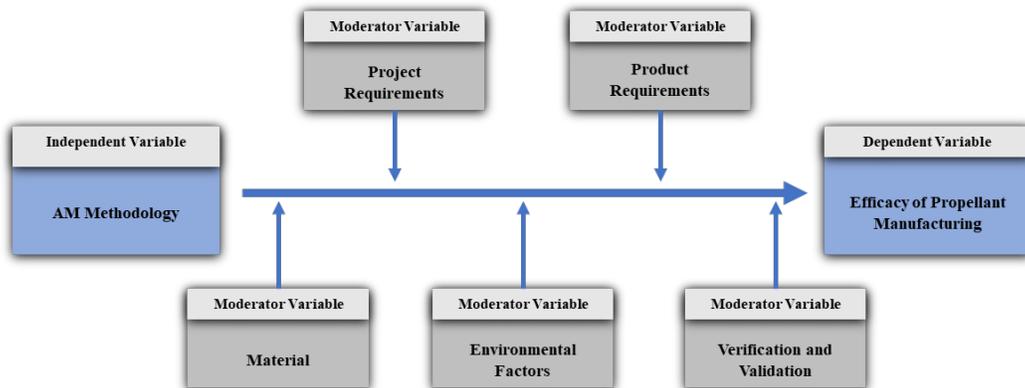


Figure 3. Conceptual Framework: EMAM Study Viewpoint

Figure 4 is a visualization of the comprehensive or AM conceptual framework, which illustrates the relationship between AM and the OIB initiatives.

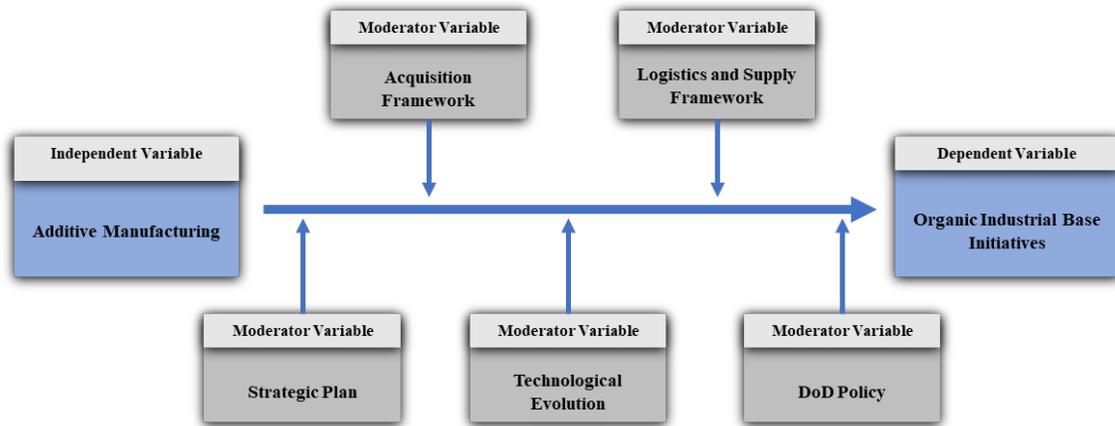


Figure 4. Conceptual Framework: AM Viewpoint

F. STUDY DESIGN

A description of the research design type and the correlative methodologies are discussed in this section.

1. Purpose

An exploratory case study analysis is employed to support the qualitative research methodology. This project explores the relationship of the AM methodologies, Direct Ink Write (DIW) and Digital Light Processing (DLP), regarding the efficacy of propellant manufacturing. In addition, the correlation of AM to the OIB initiatives is discussed comprehensively.

2. Research Approach

Multiple facets are considered to identify a research approach:

1. The questions evaluate the benefits, constraints, and BTI associated with AM and the EMAM project.
2. The authors of this CAP are affiliated with the organization facilitating the research, NSWC IHD. The primary factors for the research method selection and analysis validation stem from the project objectives.



3. The authors of this CAP deem the exploratory qualitative analysis appropriate to evaluate the benefits and constraints of AM with respect to the DOD and NSWC IHD strategic objectives.

3. General Details

This section provides an overview of the time horizon, units of analysis, and the study settings applicable to this CAP.

- **Time horizon:** A cross-sectional approach is utilized because of the EMAM study schedule and time constraints.
- **Unit of analysis:** The following assessment tools are employed to support a systematic evaluation: BTI rating scale, manufacturing readiness levels (MRLs), technology readiness levels (TRLs), evaluation, and feedback.
- **Study setting:** The research was conducted in multiple settings: NSWC IHD AM laboratory, teleconferences and meetings, discussions, and the CAD/PAD Technical Exchange Workshop.

a. Case Study Development

The analysis is derived from primary and secondary sources: NSWC IHD AM laboratory documents, publications, and literature documents. The authors of this CAP utilized the Naval Postgraduate School thesis template to compile the data and analysis. Next, the authors evaluated the data and applied MRL and TRL ratings based on the previously mentioned criteria. The MRL rating system is derived from the *2020 Manufacturing Readiness Level (MRL) Deskbook* (Office of the Secretary of Defense [OSD] Manufacturing Technology Program & Joint Service/Industry MRL Working Group, 2020). The MRL rating criteria are captured in Table 1.



Table 1. MRL Summaries. Source: OSD Manufacturing Technology Program & Joint Service/Industry MRL Working Group (2020).

MRL	Description
1	Basic manufacturing implications identified
2	Manufacturing concepts identified
3	Manufacturing proof of concept developed
4	Capability to produce the technology prototype in a laboratory environment
5	Capability to produce prototype components in a production-relevant environment
6	Capability to produce a prototype system or subsystem in a production-relevant environment
7	Capability to produce systems, subsystems, or components in a production-representative environment
8	Pilot line capability demonstrated; ready to begin LRIP
9	LRIP demonstrated; capability in-place to begin FRP
10	FRP demonstrated and lean production practices in-place

The TRL rating is derived from the *Technology Readiness Assessment Guide* (Government Accountability Office [GAO], 2020). The TRL rating criteria are provided in Figure 5.



Level	Definition	TRL Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include the integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	The Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem model or prototype demonstration in a relevant environment.	A representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluations of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system has proven through successful mission operations.	The actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Figure 5. TRL Ratings. Adapted from GAO (2020).

b. Barriers to Implementation Analysis Development

The BTI analysis is derived from primary and secondary sources: NSWC IHD AM laboratory documents, publications, and literature. A BTI template was developed, which outlines the factors, subfactors, areas of analysis, and manufacturing methodologies, as illustrated in Figure 6.



Factor	Sub-factor	Area of Analysis	DIW	DLP	Trd	Evidence
AM Technology Factors	Hardware Compatibility Ability to support the manufacturability of propellant	Product manufactured within specifications				
	Software Compatibility Ability to support an optimized design with considerations for design, shape and topology optimization	Analytic and Decision Support tools streamlined the design process				

Figure 6. BTI Template

Figure 7 depicts the BTI rating scale. A rating scale of 1–5 enables consistent measurement and standardization. The CAP authors indicated the areas of analysis for each manufacturing methodology. The application of a rating and evidence substantiate the area of analysis.



Figure 7. BTI Scale

c. Strengths, Weaknesses, Opportunities, and Threats Analysis Development

The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis is derived from primary and secondary sources: NSWC IHD AM laboratory documents, publications, and literature documents. The analysis is compiled in a SWOT analysis template, as illustrated in Figure 8.





Figure 8. SWOT Analysis Template

d. Sensitivity Analysis Development

The template illustrated in Figure 9 was developed to support the analysis. A weight was assigned to each key performance indicator and rating method.

Options	Weight	Traditional	Direct Ink Write (DIW) (AM)	Direct Light Processing (DLP) (AM)	Replace RDX in LOVA-Style Propellant (Traditional)
Cost	5				
Schedule	5				
Performance	5				
Risk	5				
MRL	5				
TRL	5				
BTI	30				
SWOT	15				
Quality	5				
Reliability	5				
Maintainability	5				
Availability	5				
Operability	5				
TOTAL					

Figure 9. Sensitivity Analysis Template



G. BENEFITS AND LIMITATIONS

The authors of this CAP received only limited access to data due to the following constraints:

- The Distribution A assignment is prohibitive, and the authors could only access limited data.
- The EMAM materials qualification and DVT are incomplete; therefore, the final recommendation is based on a narrowed perspective.

H. ORGANIZATION OF THE PROJECT

Chapter I provides an overview of the comprehensive and EMAM problem statements, research purpose, methodology, aim, questions, conceptual framework, study design, benefits, and limitations.

Chapter II is a discussion of the AM milestones and DOD AM applications.

Chapter III is an explanation of the OIB risks and correlative AM benefits.

Chapter IV is a review of the EMAM case study.

Chapter V is an examination of the EMAM case study through an evaluation of the SWOT and BTI analyses.

Chapter VI provides the EMAM case study decision criteria, summary, and recommendations.



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II. BACKGROUND

The AM process is derived from layer-based principles (Mahmood et al., 2022). According to Mahmood et al. (2022), the AM paradigm involves a set of transformational technologies and processes. The AM technology expansion from rapid prototyping to practical applications fosters innovation in both the commercial and DOD industries (Mahmood et al., 2022). The progression of technology is signified not only by the colloquial terminology, which corresponds not only to the end-use application or manufacturing process, but also to the societal impact and implications. The AM technology benefits are derived from the inherent trait—flexibility—which fosters optimization and sustainability (Eyers et al., 2018). The simplification of the manufacturing process supports design, material, project, environmental, and cost optimization. The constraints of manufacturing are addressed as AM technology evolves.

A. AM MILESTONES

Figure 10 provides an overview of 3D printing history. A major AM milestone occurred in 1984, with the invention of stereolithography, which is the technology used to create a 3D object from a picture. As indicated in Figure 10, the medical industry created organs utilizing 3D technology in the 1990s. Another significant milestone was the do-it-yourself kits, which were released in the early 2000s. In 2011, the first 3D robotic aircraft and printed car were released as a result of the 3D technology evolution. One of the most memorable 3D innovations occurred in 2020, when the global COVID-19 pandemic highlighted the importance of AM because of its ability to support supply chain issues. AM is supportive of reactive and proactive supply chain Issues, such as the face shield and mask shortages during the pandemic. According to Hanaphy’s 2022 article, X-Bow Systems debuted solid propellant, which was manufactured using AM technology (Hanaphy, 2022). The maturation of AM in the private sector has inspired adaptation in the DOD.



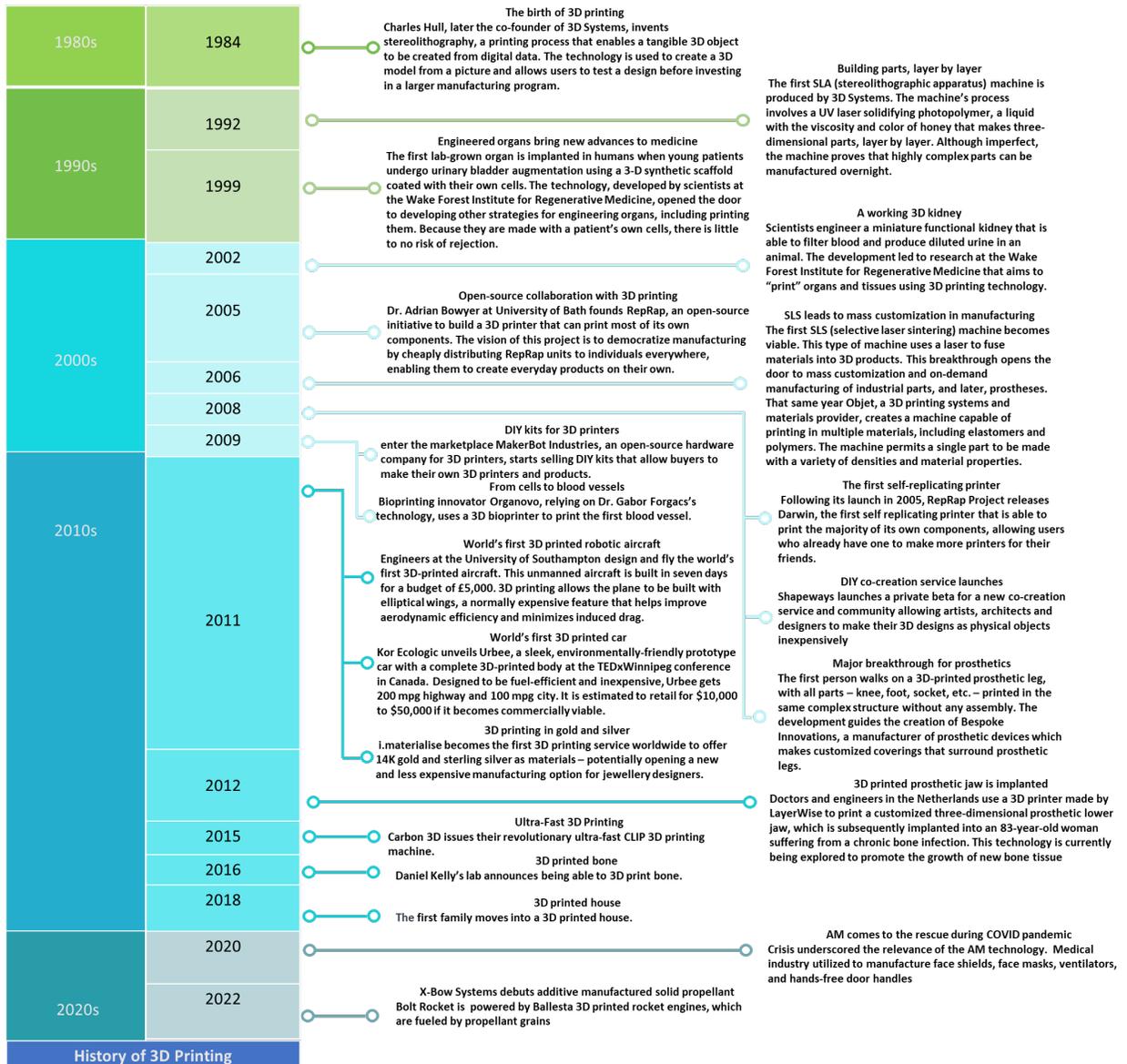


Figure 10. Developments in AM. Adapted from CloudTweaks (2015), Kamara and Faggiani (2021).

B. ADDITIVE MANUFACTURING APPLICATIONS

The widespread use of AM in the commercial industry is the catalyst for DOD adoption. AM applications are employed throughout the joint service. This section provides an overview of AM examples that strengthen the supply and logistics chain and incorporate design efficiencies.



1. Mine-Resistant Ambush-Protected Vehicle

The Mine-Resistant Ambush-Protected vehicle operations and sustain concerns were addressed using AM. One example is the door design rendered the vehicle incapable of supporting the mission in certain cases. The weight of the door was not compatible with the hinge design. AM provided a viable design solution for the hinges, which reduced the stress by half. Design optimization is an AM benefit, which is evidenced by the ability to print the hinge as one piece versus seven (Spurgeon, 2019).

Another noteworthy AM solution occurred in 2017. The replacement of the fire suppression caps was delayed because of the cumbersome acquisition process. The mission readiness is compromised with these safety critical items. Without the devices —the MRAP is unable to support mission. The AM technology mitigated the risk of a supply chain disruption. The caps were produced utilizing AM until the replacement parts were available (Suits, 2019).

2. Naval Air Systems Command

AM allows for the optimization of resources and addresses quality issues. AM applications are currently in use by the Naval Air Systems Command (NAVAIR) Air Vehicle Modification and Instrumentation group. The group printed several ancillary parts, such as antenna covers and mechanical spacers to perform form and fit checks (Naval Air Warfare Center Aircraft Division Public Affairs, 2014). In addition, the NAVAIR Innovation lab utilized AM to develop a port cover for the AV-8B Harrier's F402 engine. The lead time for the part was more than 1 year. The part is now produced at a fraction of the cost. The AM team was able to resolve the backlog within days (Cooper, 2022).

3. X-Bow Systems

X-Bow Systems developed a solid propellant rocket and propellant referred to as the Bolt. The successful debut resulted in contracts from agencies, such as the Defense Research Projects Agency and U.S. Air Force Research Lab. The design optimization of the X-Bow rocket and propellant manufacturing allows for rapid iteration and



customization to meet the mission parameters (Hanaphy, 2022). Innovations of this type will potentially lessen the United States' foreign dependency.

4. Amphibious Assault Ship LHD 5

USS *Bataan* (LHD 5) is the first Navy ship to install a permanent metal 3D printer aboard (Blenkey, 2022). A 3D technology, Meltio3D and the Haas TM-1 computer are proven to operate reliably while afloat. A 3D printer, which produces polymeric components, was also installed. The manufacturing capability promotes self-sustainment within the ship, SCR, and increases the ship's operational availability.

These projects highlight the AM benefits and contributions to the OIB restorative initiatives. Each supports SCR and self-sustainability through the incorporation of AM.



III. LITERATURE REVIEW

Chapter III provides a discussion of the root causes of the OIB deficiencies, the impact of AM to the logistics and SCR efforts, and the policies to support the incorporation of disruptive technology to restore the OIB.

Sharma et al.'s (2021) research suggested that outsourcing seems to be an effective solution; the current geopolitical issues and world health crisis expose the vulnerability of a globalized trade policy and partnerships. As a result, the United States and other countries are reevaluating their political and financial policies and the importance of self-sustainment. These drivers have perpetuated an increase in the economic nationalism ideology. The urgency to facilitate self-sustainability has necessitated a requirement for R&D and manufacturing initiatives.

Systematic and cyclic factors accelerated the demise of the U.S. OIB (Interagency Task Force, 2018). The manufacturing demands, coupled with the political, economic, and technological revolution, forced the manufacturing industry to reevaluate its business strategies. While these factors are not all-encompassing, each is detrimental and contributes to the decline of industry. Business strategies were revised to incorporate trade-offs, such as the outsourcing of manufacturing, which involved the relocation and closure of manufacturing facilities, albeit these short-term solutions did not account for the long-term ramifications to the national economic structure and security posture (Mehta, 2018).

According to Altman (2020), the inherent risk of globalization was not considered in depth. In retrospect, little forethought was given to national security and socioeconomic implications concerning the DOD objectives, manufacturing strategies, and import policies. A culmination of the political landscape and COVID-19 pandemic, which have heightened the country's economic issues, have brought the consequences of globalization to the forefront (Altman, 2020).

The deindustrialization of manufacturing was a critical milestone that led to import dependency (Interagency Task Force, 2018). The U.S. MIB has experienced a gradual decline for 5 decades. The most significant decline occurred in 2010, as depicted in Figure



11. According to the *Fiscal Year 2020 Industrial Capabilities: Report to Congress*, the manufacturing industry accounted for 40% of the gross domestic product (GDP) in the 1960s, which decreased to 12% as of 2020. This equates to over 5 million manufacturing jobs from 2000 to 2015 (OSD A&S Industrial Policy, 2021).

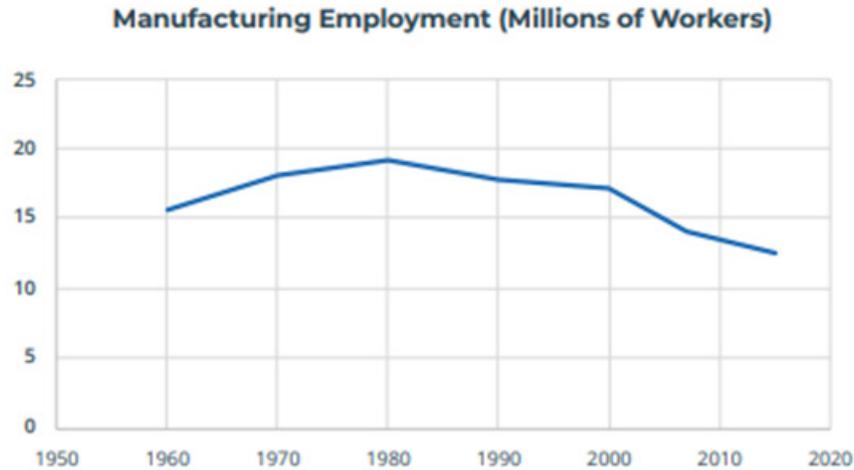


Figure 11. GDP Decline in Manufacturing. Source: OSD A&S Industrial Policy (2021).

The ascension of globalization and neoliberalism is contemporaneous with the decline in manufacturing (Interagency Task Force, 2018). The shift in government policies to align with the emergence of electronic commerce, the information technology revolution, and economic factors resulted in globalization. While globalization is more cost-effective for corporations, shareholders, and consumers because of the lenient labor and environmental regulations, these benefits have become a constraint to the U.S. economy and national security. The residual effects of the unbalanced U.S. domestic versus international manufacturing scale are present throughout the country to this day. The resulting domino effect caused disruptive political, socioeconomic, and economic strain throughout regions in the United States (Interagency Task Force, 2018).



There are varying consequences of globalization, such as the increased risk of cybersecurity attacks, weapons proliferation, and the potential for additional global health crises. The widespread effect of globalization not only impacts the economy but also poses a national security threat (Davis, 2003). In terms of manufacturing, globalization liberalizes imports and exports. This free-trade approach with limited government intervention has led to China's global manufacturing dominance. The detrimental effect of these neoliberalism-influenced and free-trade approach policies is evidenced by the current OIB infrastructure. The collective short-term financial gain and savings for U.S. corporations, shareholders, and consumers are minute in comparison to the long-term damage to the OIB infrastructure. As a result, the United States is reassessing its dependence on other countries. This new mindset of economic nationalism has prompted DOD and commercial research initiatives to advance manufacturing in the United States (OSD A&S Industrial Policy, 2021)

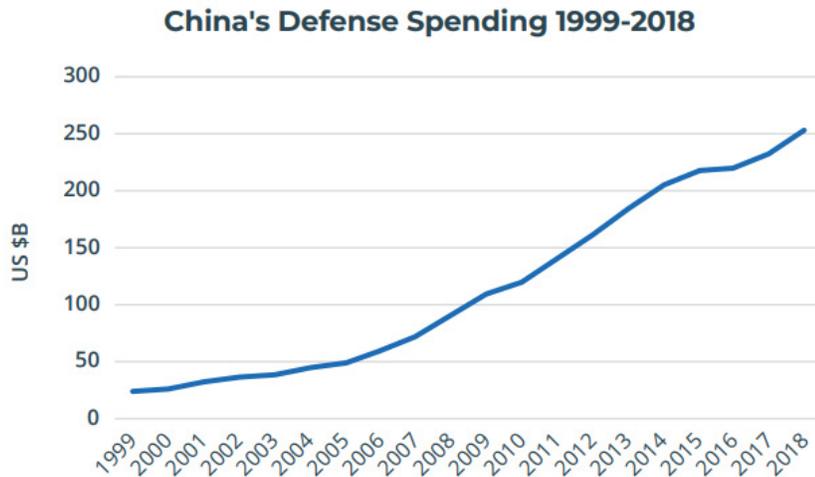
A. ORGANIC INDUSTRIAL BASE

The decline in the U.S. OIB correlates with the ascension of market globalization. Furthermore, the recent global COVID-19 pandemic, coupled with political and economic circumstances, highlights the deficiencies in the supply chain infrastructure (OSD A&S Industrial Policy, 2021). The OIB subsets, the DIB and MIB, have experienced a significant decline. While globalization is the primary catalyst for this conundrum, it is not all-encompassing. Political, economic, and technological determinants facilitated globalization in the United States, which has resulted in import dependency. These catalysts are twofold: first, in terms of attributing to the defense and manufacturing capability gap in the United States, and second, in respect to functioning as a basis for the strategic initiatives to revive the industry.

The United States' DIB is known for its ascendancy. Furthermore, the MIB is attributable to the defense infrastructure. The 2021 OSD(A&S) Industrial Policy report suggested that China continues to increase its annual military budget, as indicated in Figure 12. The U.S. defense strategy must focus on its post existence. China is a primary source of critical resources, such as the raw materials and chemicals required to produce



propellants, such as lanthanide. It is strategically imperative to implement measures to safeguard national security, considering the current geopolitical climate (OSD A&S Industrial Policy, 2021).



Data Source: World Bank
<https://www.macrotrends.net/countries/CHN/china/military-spending-defense-budget>

Figure 12. China’s Multiyear Financial Defense Strategy. Source: OSD A&S Industrial Policy (2021).

Notwithstanding the increase in adversaries, U.S. complacency, coupled with distractions of the Iraq and Afghanistan wars, impeded the implementation of a strategic plan. Presently, the strategic imperatives to advance the DIB include a risk management framework to restore industrial readiness. According to a White House (2022) report titled *Safeguarding Our National Security by Promoting Competition in the Defense Industrial Base*, the framework must emphasize competitiveness, oversight of mergers, small business opportunities, and supply chain resilience.

The National Defense Industrial Association (2023) concluded that the current state of the U.S. manufacturing industry is an indicator of its competitive disadvantage. U.S. DIB competitiveness is stymied by bureaucratic processes and policies. Subsequently,



there is a reduction of new entrants in the DIB, as shown in Figure 13. The shrinking industrial base inhibits competition, diversity, and innovation (NDIA, 2023).



Figure 13. New Entrants in the DIB. Source: NDIA (2023).

The research, development, and employment of the AM capability is supportive of the DIB restoration strategies. AM technology has the capability to ease the supply chain burden, reduce production costs, foster innovation, streamline operations, and sustain processes. The challenge of restoring the industrial bases, in turn, is the catalyst for R&D to advance the direct digital manufacturing paradigm, referred to colloquially as AM and 3D printing. Technological and strategic mechanisms, such as Industry 4.0, Industrial Internet of Things, U.S. national strategy, DOD AM Strategy, and Manufacturing USA are supportive of U.S. strategic objectives.

According to analysis conducted by a Reagan Institute task force, there are fundamental areas that must be addressed to revitalize the MIB. Training, incentives for domestic manufacturers, and establishing an international oversight forum to support national security policies would support the continuous improvement of U.S. manufacturing competitiveness (Task Force on National Security and U.S. Manufacturing Competitiveness, 2021). The AM paradigm is a key component in the resurgence of



manufacturing in the United States, which is often referred to as the 4th Industrial Revolution. Prospectively, the inherent characteristics of the manufacturing paradigm could foster a resilient supply chain and logistics infrastructure.

B. LOGISTICS AND SUPPLY CHAIN

The *Executive Order on America's Supply Chains*, issued by the White House on February 24, 2021, is supportive of an agile supply chain infrastructure. A more resilient supply chain will foster sustainability, strengthen national security, and cultivate economic stability. For example, the Ukrainian war has underscored the importance of a responsive supply chain. It is vital to have a manufacturing capability with the capacity to respond to national security threats, obsolescence, sole source supply, and depletion issues (White House, 2021).

The inefficiencies in the U.S. supply chain framework are a consequence of the waning U.S. MIB. Consequently, weakened national security is an implication of import dependency. Supply chain disruptions are an intractable problem within the DOD and commercial industry, as evidenced during the COVID-19 pandemic and Ukrainian war. The primary objective of the supply chain infrastructure is to enable resiliency in normal operations and heightened crises. However, the current infrastructure is resource-challenged and lacks agility. The current system is overly reliant on imports, which exposes U.S. vulnerabilities and sustainability challenges. Furthermore, the current JIT manufacturing model is incapable of supporting heightened crises.

According to Naghshineh and Carvalho (2020), AM supports the JIT model; however, the differentiating factor is that technology has an innate ability to support both proactive and reactive planning. AM is not bound by economies of scale; therefore, it is supportive of the strategic prioritization of inventory levels, with the potential to reduce the logistics footprint. The supply chain design and proactive and reactive capability attributes of AM correspond to the DOD objectives to support a resilient supply chain. The employment of integrated AM technology and processes fosters design flexibility, promotes efficiency, and facilitates redundancy and cost-effectiveness to enable the DOD competitive advantage and military readiness. Considering the current geopolitical climate,



the responsiveness of the supply chain, also referred to as SCR, is a fundamental element of the DIB initiatives. A dynamic SCR infrastructure would address the supply chain issues by thwarting the parts obsolescence, sole source supply, depletion, and small batch manufacturing concerns. Prospectively, it could decrease the total ownership costs of systems. AM contributes to cost reductions by enabling a noncomplex and agile supply chain infrastructure. A noncomplex infrastructure is achieved through logistics footprint reduction and the simplification of product designs (Naghshineh & Carvalho, 2020).

C. DOD INSTRUCTION 5010.44: INTELLECTUAL PROPERTY ACQUISITION AND LICENSING

According to the DOD Instruction 5010.44, the overall objective is to balance the interests of the U.S. government and industry regarding IP. The instruction also emphasizes the importance of an effective IP strategy, which considers the project requirements and triple constraints. Thus, ensuring the system will perform per the specifications throughout its life cycle and encouraging technological advancements. (Office of the Under Secretary of Defense for Acquisition and Sustainment, 2019).

D. DOD INSTRUCTION 4120.24: THE DEFENSE STANDARDIZATION PROGRAM

DOD Instruction 4120.24 addresses materials standardization, including information technology and facilities. These areas must be addressed throughout the acquisition process (Department of Defense, 2018). This is especially important as the DOD adopts disruptive technologies like AM. The innovative technology must follow the same rigor and standards as it goes through the acquisition process.

The United States' globalized ecosystem is a root cause of the OIB deficiencies. A disruptive technology such as AM is supportive of a resilient logistics and supply chain infrastructure. An ecosystem that is both proactive and reactive will further advance the DOD SCR efforts. AM with considerations for standardization and IP concerns is a viable solution to achieve SCR.



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IV. CASE STUDY

This case study will explore the EMAM project. An assessment of study highlights the benefits and constraints of nontraditional manufacturing and AM.

A. SITUATION

The Cartridge Actuated Device/Propellant Actuated Device (CAD/PAD) Joint Program Office (JPO) requested an EMAM project review to determine the path forward and transition the technical baseline to the Program Management Agency (PMA) 007.

B. INTRODUCTION

On an early spring morning in 2016, Bob Urban, the program manager from Manufacturing Technology Systems (MTS), and William Smith, the senior CAD/PAD engineer from the NSWC IHD, were discussing the HES 5808 anomalies. Earlier that morning, Urban and Smith informed CAD/PAD JPO Program Manager Trent Mahoney and Deputy Program Manager Foster Harrison about the concern over the high rate of anomalies.

With well over 125 years of manufacturing experience under its belt, NSWC IHD was faced with a dilemma. For 50 of those years, the HES 5808 had been in use. For years, the CAD/PAD program had struggled with HES 5808 propellant production issues related to meeting delivery schedules and vendor and IP transitions. The organization contemplated this issue regarding the HES 5808 product quality, the shrinking DOD industrial base, and IP rights.

C. BACKGROUND

The EMAM R&D study evaluates the efficacy of the AM methodologies, DIW and DLP, in relation to the manufacturing of propellant. The catalysts for the study are the high rate of defects and constraints of traditional manufacturing. The HES 5808 is a critical component of the M91 Impulse Cartridge, which is utilized in the AV-8, F-5, F-16, and T-38 aircrew escape systems. The project sponsors include the following:



1. Navy Manufacturing Technology, Manufacturing Technology Program Office/ONR
2. Naval Sea Systems Command 05T
3. CAD/PAD JPO

The HES 5808 is a high temperature-resistant and ammonium perchlorate-based composite propellant utilized in the aircrew escape system. The high temperature resistance is a safety requirement, as it ensures the propellant can remain stable in emergency situations. It is utilized in the M91, M93, and M73 cartridges and the F-18 canopy remover. The motor performance is determined by the HES-5808 propellant grain shape and size. The propellant grains are cast-molded, with the viscosity of hard rubber or plastic. The propellant is manufactured separately and loaded into a cartridge, also referred to as cartridge-loaded or freestanding grains, as illustrated in Figure 14. The existing HES 5808 is the only formulation qualified for use in the CAD/PAD M91, M93, and M73 cartridges and the F-18 canopy remover.

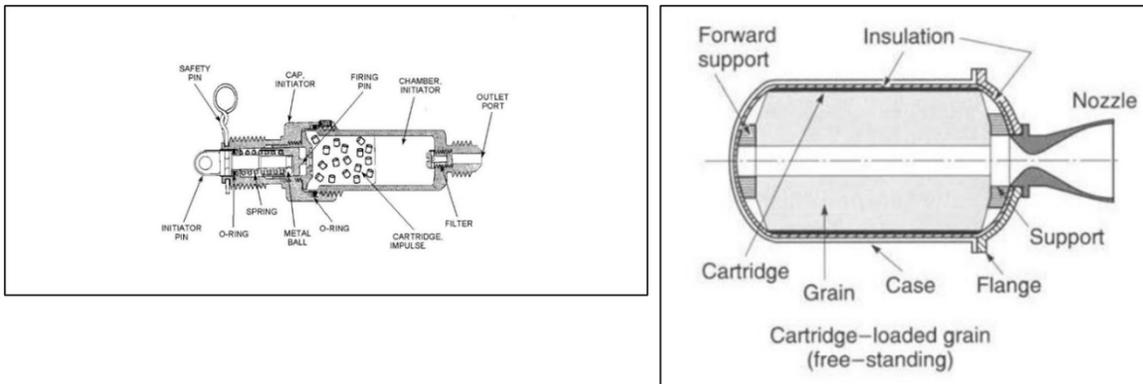


Figure 14. HES 5808 Cartridge-Loaded Grain. Source: Aerospace Notes (n.d.), Naval Air Systems Command (2023).

1. Key Performance Parameters

Based on Weapon Specification DTL-WS-35770, the key performance parameters are the formulation, weight tolerances, ingredient lot, and form and dimensions, as indicated in Table 2.

Table 2. HES 5808 Key Performance Parameters. Source: Naval Surface Warfare Center Indian Head Division (NSWC IHD, 2015).

#	KPP	Threshold/Objective
1	Formulation	Ingredient weight percentages shall be 78–86% Ammonium Perchlorate, 10–16% Cellulose Acetate, and 3–5% Methyl Phthalyl Ethyl Glycolate
2	Weight Tolerances	Minimum accuracy of $\pm .05\%$ within the formulation weight ranges
3	Ingredient Lot	Cross blending of ingredients from different lots is not permitted
4	Form and Dimensions	Grains' geometry shall be right circular cylinder with open cylindrical perforation(s) parallel to the longitudinal axis of the grain and evenly spaced across the circular face of the grain. The grain surface shall be smooth.

a. Work Breakdown Structure

Solid propellants are made up of three basic ingredients: oxidizer, fuel, and binder, as illustrated in Figure 15, HES 5808 Work Breakdown Structure. Chemical composition and geometry are key considerations when developing energetic material. In the event of an emergency, the HES 5808, EM, or stored energy triggers a series of events to eject the aircrew members from the aircraft.

An oxidizer is a substance that promotes combustion (Ashish et al., 2019). The binder serves as a bonding agent for the fuel, which is oxidized in the combustion event (Chaturvedi, & Dave, 2019). The fuel is the catalyst that works in conjunction with the oxidizer and binder to produce consistent burn (Chaturvedi & Dave, 2019). The key attributes are burn rate, oxygen balance, density, and heat of formation, which are defined as follows:

1. *Burn rate* is a measurement of the rate of combustion (Chaturvedi & Dave, 2019).



2. *Oxygen balance* is the measurement of oxygen in a compound. There is direct correlation between the concentration of oxidation and propulsion (Ashish et al., 2019).
3. *Density* is a measure of explosive potential by volume (Ashish et al., 2019).
4. *Heat of formation* is a measurement of the total energy and temperature released during combustion (Chaturvedi & Dave, 2019).



Figure 15. HES 5808 Work Breakdown Structure. Adapted from Ashish et al. (2019), Chaturvedi and Dave (2019).

2. History

Throughout the years, the ownership of the HES 5808 propellant formulation and the associated IP rights transitioned several times due to company acquisitions, as illustrated in Figure 16. The limited number of HES 5808 consumers is not economically feasible from the vendor's perspective. The government was Alliant Techsystems' only HES 5808 customer at one point. In 2004, the company determined it could no longer manufacture the propellant based on the original terms. Therefore, Alliant Techsystems granted NSWC IHD the government exclusive IP rights to manufacture HES 5808. NSWC IHD successfully assumed the role of manufacturer. Eventually, Alliant Techsystems sold the formulation and IP rights to MTS. NSWC IHD discontinued the manufacturing and awarded a sole source contract to MTS in 2021 (T. Bryant, email to author, April 3, 2023). The uncertainty regarding the IP rights was resolved in 2023, when the IP rights were granted to NSWC IHD due to the organization's significant contribution to the HES 5808 formulation. NSWC IHD intends to resume the manufacturing of HES 5808 (B. Kerlin, email to author, August 21, 2023).

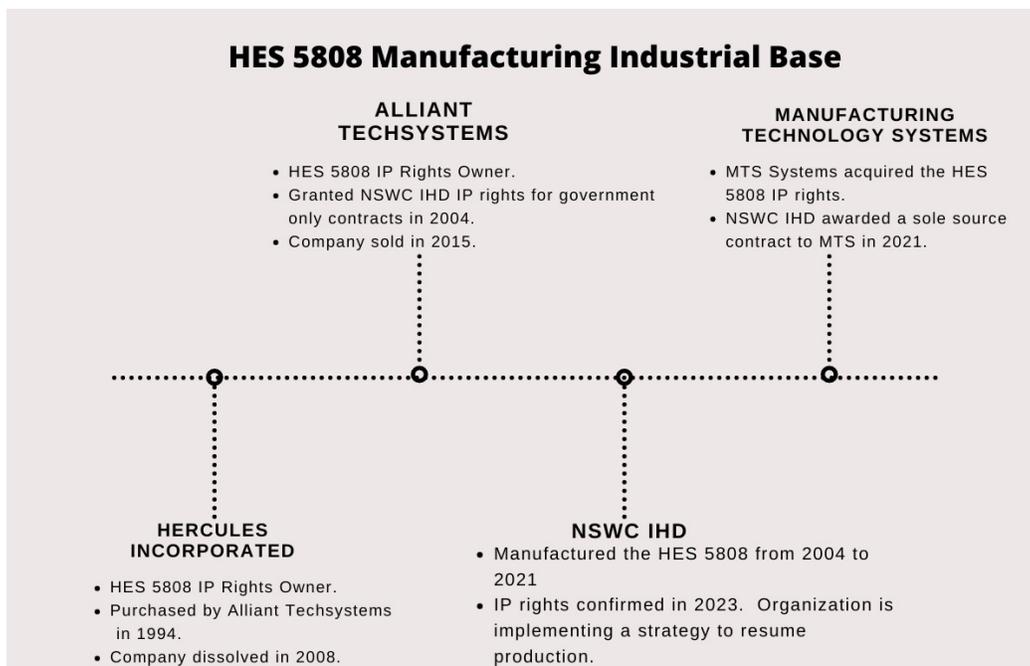


Figure 16. HES 5808 Industrial Base Timeline. Adapted from T. Bryant (email to author, April 3, 2023).



The CAD/PAD JPO and NSWC IHD conducted an assessment that resulted in several research efforts:

1. AM research: The ONR and NSWC IHD conducted the advanced manufacturing R&D of the HES 5808 propellant, which is referred to as the EMAM project.
2. Traditional manufacturing research with HES 5808: MTS and NSWC IHD researched the traditional manufacturing of the HES 5808 formulation.
3. Traditional manufacturing research with new formulation: NSWC IHD conducted an R&D study referred to as the *Proof of Principle Study to Replace RDX in LOVA-Style Propellant Formulations* (Allen & Bichay, 2017). The objective of the study was to identify a feasible HES 5808 alternative to support the traditional manufacturing process.

D. TRADITIONAL MANUFACTURING

The HES 5808 propellant is a specialized formulation that must be produced in a controlled environment. The constraints of traditional manufacturing result in waste and quality inconsistencies. The manufacturing capability gap results in production issues related to meeting the delivery schedules and IP concerns because of vendor transitions. There is a high rejection rate when HES 5808 is produced via the traditional manufacturing method due to physical anomalies such as cracking, curved grains, small pits, and dilated/collapsed perforations, as illustrated in Figure 17. The primary issue is the internal cracking inside the grain between the perforations, which can lead to performance degradation and waste. The inconsistency in quality directly correlates to performance.



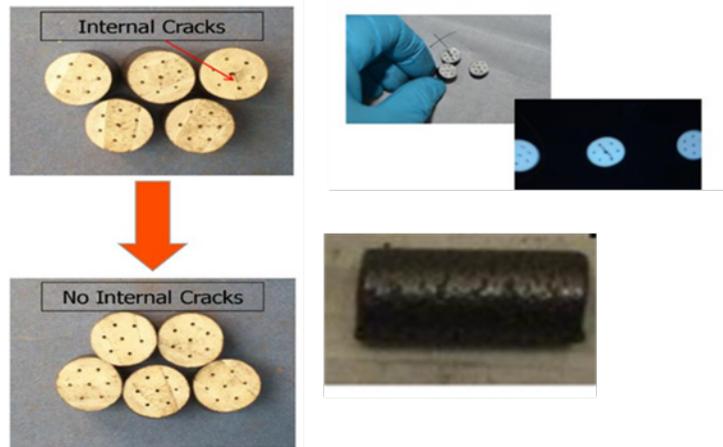


Figure 17. Traditional Manufacturing Anomalies.
Source: Parker and Knott (2018).

1. Traditional Manufacturing Process

The traditional manufacturing method primarily involves three steps:

1. Mix the ingredients with solvent to form a malleable dough.
2. Extrude the dough into gun-type propellant grains.
3. Dry the grains to remove the excess solvent and moisture.

2. HES 5808 Traditional Manufacturing Research

MTS and NSWC IHD conducted research and testing. The test results were briefed to the stakeholders in 2018.

Closed vessel testing involves burning a controlled amount of propellant based on a set of predetermined specifications in a vessel. The HES 5808 closed vessel testing demonstrates quality and consistency issues within the same production lot via the traditional manufacturing process. As illustrated in Figure 18, the outliers are an indication of the inconsistencies of the traditional manufacturing process. Ideally, the sample results should be closer or tighter in formation.

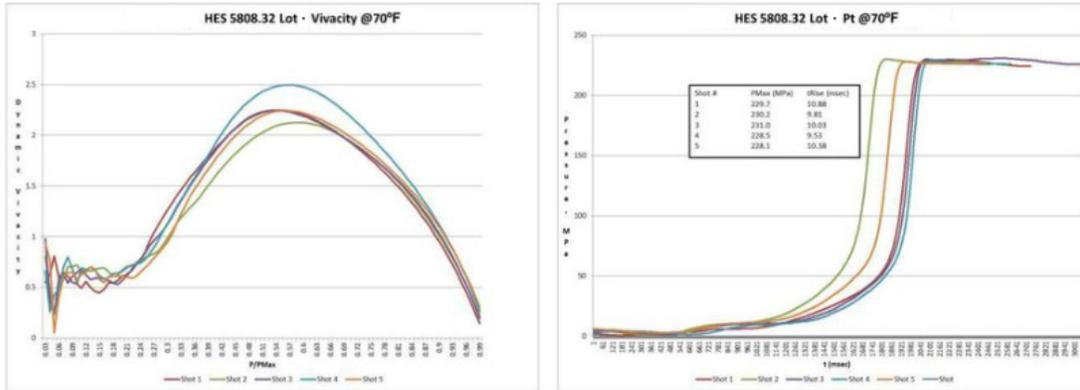


Figure 18. Closed Vessel Testing. Source: Parker and Knott (2018).

The HES 5808 geometry varies depending on the end use/cartridge application. The cracking and rough surface issues are more prevalent in the larger geometries (Parker & Knott, 2018). The HES 5808 traditional manufacturing research focused on the propellant formulation, mixing parameters, solvent system, and blocking. The research team analyzed the solids fill percentage and the plasticizer/polymer ratio of the propellant formulation. An assessment of the mixing parameters with a focus on the order of ingredients and ingredient preparation was completed. Next, the research team analyzed the solvent system with a focus on the solvents used, ratio, and loading. The team determined that three of the propellant ingredients can be adjusted as explained in Table 3. The ratio of ammonium perchlorate and methyl phthalyl ethyl glycolate (MPEG) was investigated in the study.

Table 3. HES 5808 Primary Ingredients. Source: Parker and Knott (2018).

Ingredients	Weight Percent
Ammonium Perchlorate	78 - 86
Cellulose Acetate	10 - 16
Methyl Phthalyl Ethyl Glycolate	3 - 5
	Total 100%
Graphite	0.40 Max

a. Quality

The formula modifications yielded the results in Table 4.

Table 4. Formulation Type and Results. Source: Parker and Knott (2018).

Formulation	Ratio	Results
High Solids Fill	High Plasticizer/ Polymer Ratio	Improved Internal, Poor External Quality
High Solids Fill	Lower Plasticizer/ Polymer Ratio	Poor Internal, Improved External Quality
Low Solids Fill	Lower Plasticizer/ Polymer Ratio	Improved Internal and External Quality

Modifications to the formulations to high solids fill, high plasticizer/polymer ratio improved the internal issues, but the external quality did not improve. The internal cracking is illustrated in Figure 19. Three of the 30 grains have internal cracking, which is indicated by the circles.



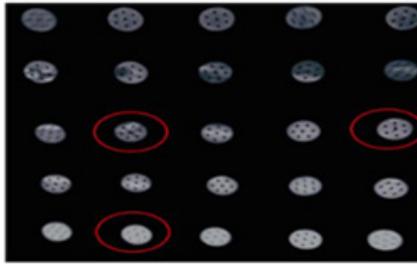


Figure 19. High Solids Fill With High Plasticizer Results. Source: Parker and Knott (2018).

Modifications to the formulations with high solids fills and lower plasticizer/polymer ratio improved the external issues, but the internal quality did not improve. As illustrated in Figure 20, 27 of the 30 grains had internal cracking. In this case, the circled grains do not have cracks.

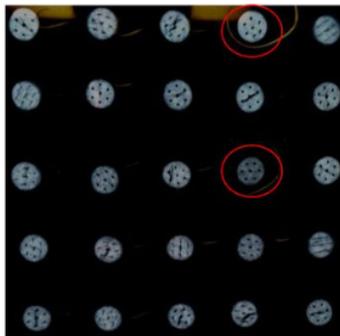


Figure 20. High Solids Fills With Low Plasticizer Results. Source: Parker and Knott (2018).

Modifications to the formulations with low solid fills and lower plasticizer/polymer ratio improved both the external and internal quality. The external and internal improvements are depicted in Figure 21.

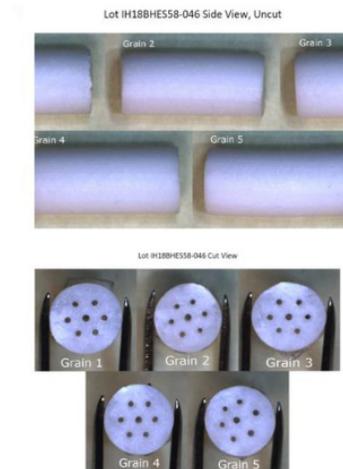


Figure 21. Low Solids Fills With Low Plasticizer Results. Source: Parker and Knott (2018).

The R&D of multiple iterations of the formulation was conducted throughout the years. Acetone and ethanol were used to manufacture the HES 5808 propellant in the past. However, there is an increased risk when handling and processing due to the volatility of the solvent. Other iterations of the formula were researched to identify a less volatile solvent: ethyl lactate, butyl acetate, and the combination of both, an Ethyl LactateButyl Acetate. Recently, the solvent is a combination of ethanol, acetone, and Ethyl LactateButyl Acetate solvent with varying ratios and loadings.

Per the MTS and NSWC IHD research findings, the mix preparation and order in which the ingredients are added have significant impact on the overall quality. The research concluded that combining the ammonium perchlorate, MPEG, and process solvents requires a 16-hour wicking period. The solvent system and plasticizer, MPEG are key ingredients, which solubilizes the cellulose acetate. There is a notable improvement in the strength of the propellant strands during extrusion, when using this method. In addition, a less volatile solvent is required.

The effective mixing and propellant-to-solvent equilibrium are crucial elements. The propellant dough must be consistent, and the dough must be mixed, and the material must be loaded in the blocking press within the predetermined time.

MTS and NSWC IHD manufactured the prospective mixtures in May 2018. The objective was to further analyze the solids-to-binder ratio, proposed ingredient preparation method, ratio of solvents, blocking preparation, and drying process.

b. Cost

The average cost per unit is \$10.00.

c. Supply Chain

NSWC IHD was the only manufacturer of the M91 cartridge as of 2004. A contract was awarded to a second source M91 manufacturer, ACME. The M91 manufacturer is responsible for loading the cartridge with the HES 5808 solid propellant as illustrated in Figure 22. MTS and NSWC IHD are both qualified HES 5808 manufacturers. MTS is the primary manufacturer. NSWC IHD is developing a strategy to resume production.

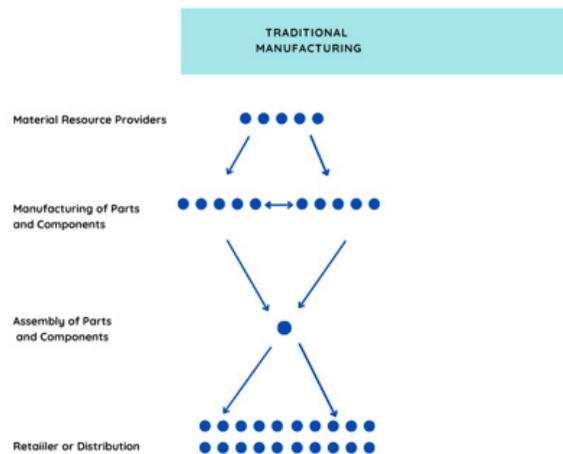


Figure 22. Supply and Logistics Framework. Adapted from Thomas and Gilbert (2014).

d. Intellectual Property Challenges

After lengthy assessment, NSWC IHD obtained the HES 5808 IP rights as result of the organization’s significant contributions. IP rights concerns are common throughout the DOD and apply to both traditional and AM.

3. Proof of Principle Study to Replace RDX in LOVA-Style Propellant Formulations

The Proof of Principle study to replace the RDX in LOVA-style propellant formulations focused on the development of a HES 5808 perchlorate-free propellant alternative. Ammonium perchlorate is an oxidizer that is commonly used in solid composite rocket/missile propellants. The HES 5808 product is comprised of up to 86% by weight of this oxidizer. The objective was to produce a similar propellant in terms of the burn rate and granulation to ensure the ballistic performance was not compromised. The formulation could potentially replace the HES 5808 in the CAD systems. Allen’s and Bichay’s research explains the alternative propellant is comprised of the following ingredients:

- Cyclotetramethylene tetranitramine (HMX)
- Nano-sized aluminum fuel
- Strontium nitrate oxidizer
- Small quantities of mixing and processing aids (Allen & Bichay (2017))

The ingredients utilized in the conventional formulations are the basis for the selection of energetic ingredients and propellants. Two formulations were developed and analyzed: nano-aluminum and oxidizer and micron-sized aluminum and oxidizer. The research results are explained in Table 5.

Table 5. LOVA-Style Formulations and Results. Adapted from Allen and Bichay (2017).

Formula	Results
Nano-aluminum and oxidizer	Increased the burn rate
Micron-sized aluminum and oxidizer	Little effect on the burn rate



a. Quality

Both nano-aluminum and micron-sized aluminum and oxidizer formulations met the readiness criteria for demonstration testing based on the performance. The burn rate and simulated ballistic performance of the replacement propellant were within ranges similar to HES 5808.

b. Cost

The cost information is not available.

c. Supply Chain

The M91 cartridge supply chain would parallel the traditional manufacturing with HES 5808. Upon successful testing, NSWC IHD would be the only qualified manufacturer of the LOVA-style formulation. The supply chain structure would be similar to the traditional manufacturing with HES 5808 as depicted in Figure 23.

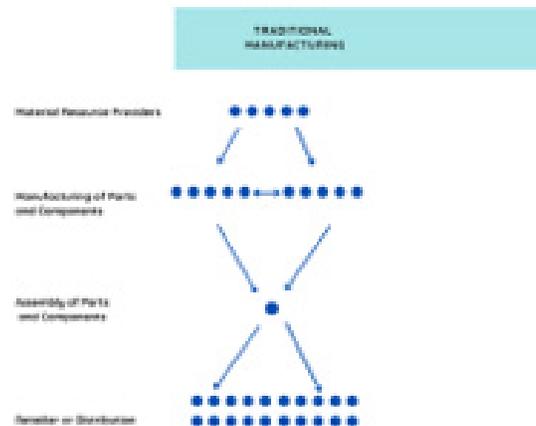


Figure 23. Supply and Logistics Framework. Adapted from Thomas and Gilbert (2014).

d. IP Challenges

NSWC IHD is the IP rights owner, and there are no IP rights concerns.

4. Risk Assessment

MRL and TRL ratings were applied as indicated in Table 6.

Table 6. Traditional Manufacturing MRL and TRL Ratings.

	Traditional Manufacturing With HES 5808	Traditional Manufacturing With LOVA Style
MRL	9	4
TRL	9	4

E. ADDITIVE MANUFACTURING

In early 2017, the ONR funded \$1,727,000 to conduct the research and feasibility analysis of AM in energetics, specifically the HES 5808 (Painter, 2022). A NSWC IHD six-member team, which was comprised of a project leader, chemical engineers, mechanical engineers, and chemists, was established (Perry, 2022). The HES 5808 was selected because of its simplistic formulation and inherent traits, such as low sensitivity to friction, impact, and static discharge. The AM methodologies, DIW and DLP, were selected as potential candidates.

1. Energetic Materials Additive Manufacturing Project Feasibility Analysis

The team conducted a feasibility analysis to determine if the HES 5808 was a viable candidate for AM manufacturing. The decision support criteria utilized to assess the project suitability is depicted in Figure 24.

1. *Quotation support* involves the evaluation of the AM hardware, methodology, and materials.
2. *Capital investment support* considers the cost, compatibility, and product specifications when assessing the AM hardware, methodology, and materials options.
3. *Process planning support* involves the project planning and resource allocation.



4. *Decision theory* assesses the options and trade-offs based on the priorities established by the stakeholders.

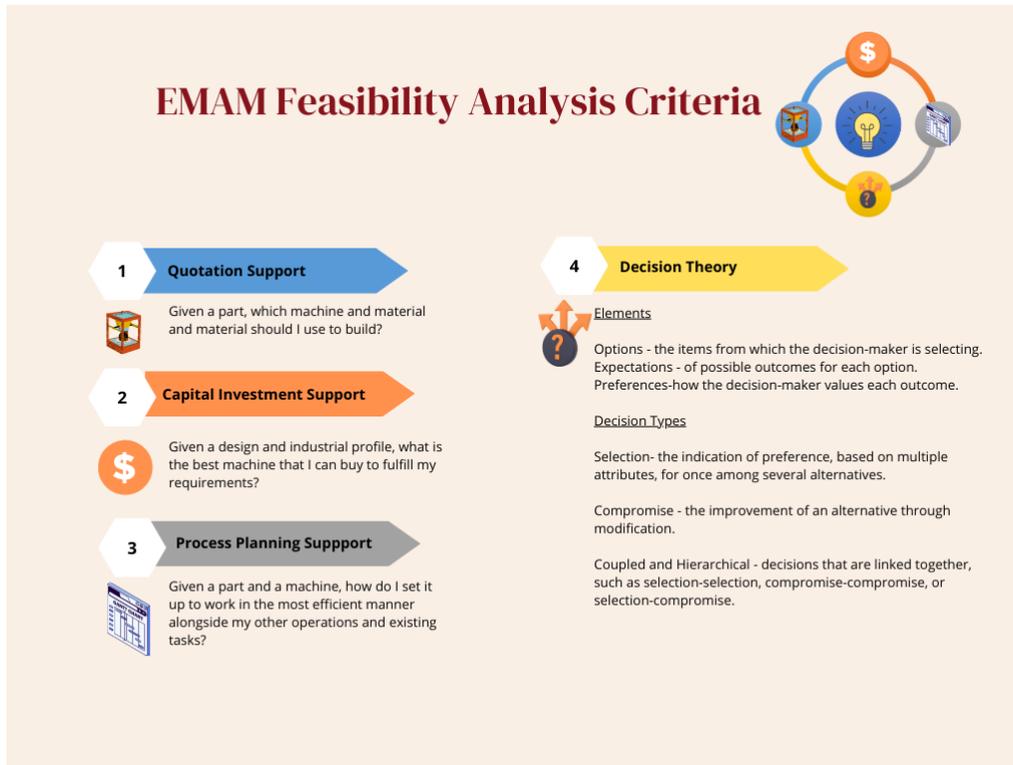


Figure 24. EMAM Project Assessment Criteria. Adapted from Gibson et al. (2021).

2. Additive Manufacturing Methodology Selection

The EMAM team’s assessment of the DIW and DLP AM methodologies is based on the criteria shown in Figure 25. This criterion is the basis for the 3D printer technology and methodology selections. The objective of the technology assessment is to identify a 3D printer and methodology that is compatible with the project requirements. Both the 3D printer and methodology must be capable of achieving the desired dimension accuracy and surface finish (Niaki & Nonino, 2018).

The geometry criteria, maximum dimension, and part complexity are evaluated to determine the compatibility with the 3D printer and methodology. The level of geometric complexity is a determining factor (Niaki & Nonino, 2018).

The performance criteria are hypothesized based on the previous research of the methodology.

An economic assessment was completed based on the criteria, running cost, post-processing cost, material cost, and equipment cost. The evaluation ensures the 3D printer and methodology will accomplish the project requirements within the cost constraints and total ownership costs.

The productivity criteria, scan speed, overhead time, and post-processing time are used to assess manufacturing time.



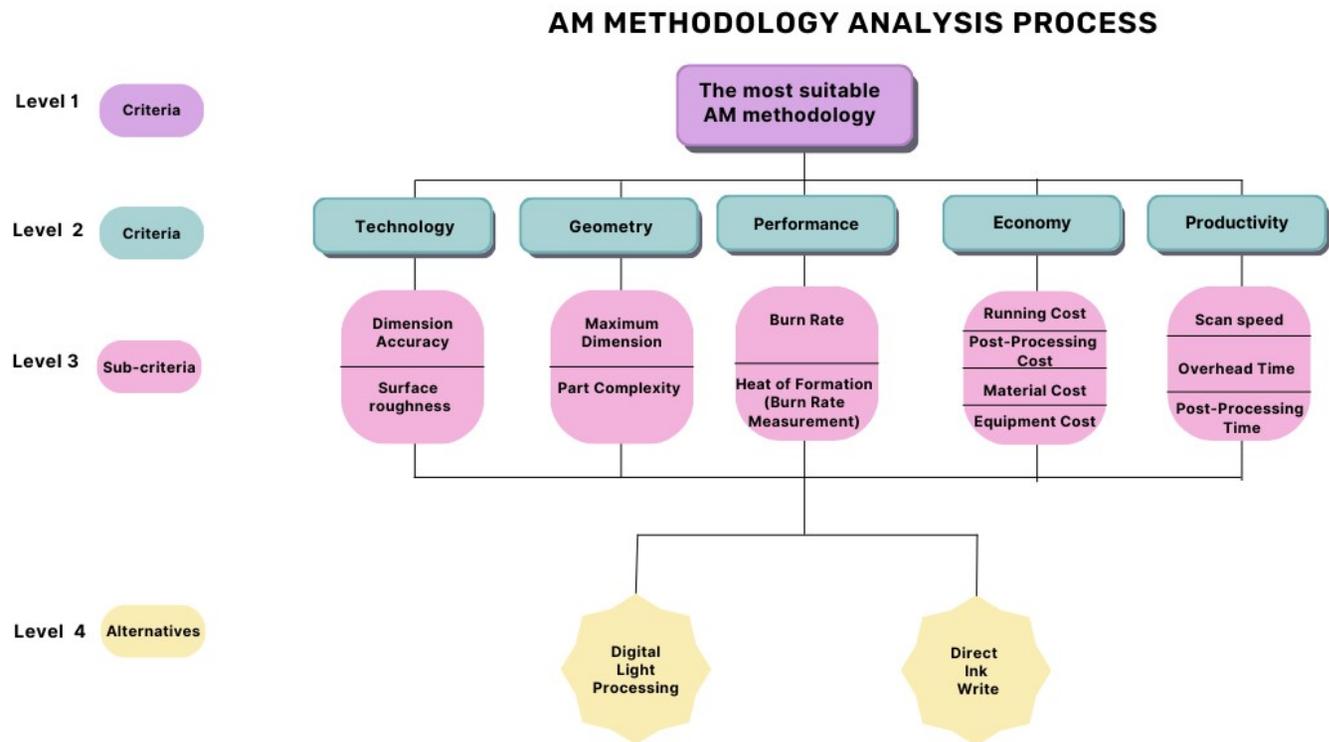


Figure 25. AM Methodology Selection Process. Adapted from Niaki and Nonino (2018).



3. Materials Analysis and Selection

The EMAM team assessed the HES 5808 product requirements and determined that a polymeric form of material is most suitable. The state of fusion, material feedstock, material distribution, basic AM principles, and process categories or methodologies are assessed based on the product specifications. The highlighted information in Figure 26 pertains to the DIW and DLP methodologies. Next, further analysis of the material assessment is reinforced in the methodology selection.

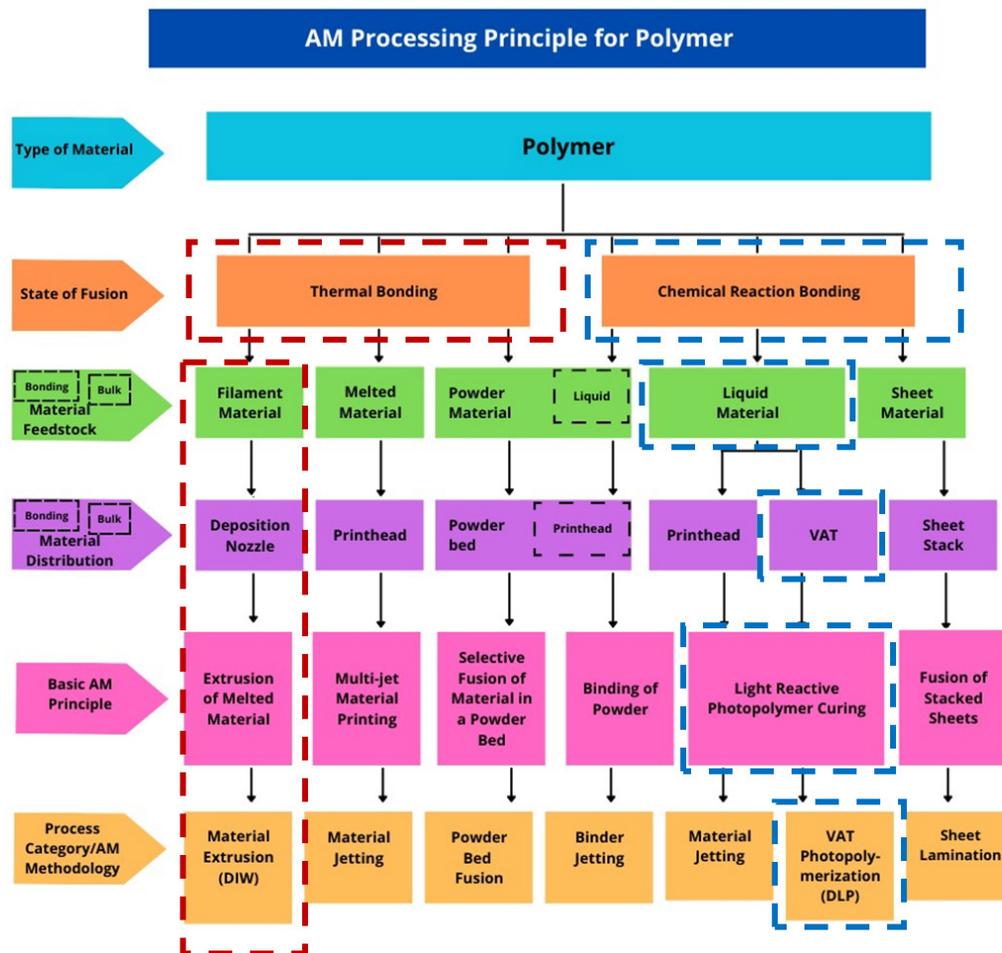


Figure 26. Polymeric Principles of AM. Adapted from Gibson et al. (2021).

4. Hardware Selection

The team conducted further analysis to select hardware to support the DIW and DLP AM methodologies. Factors such as the geometric complexity, part size, surface finish, tolerances, anticipated part life, strength, and stiffness were considered to determine the AM hardware (Gibson et al., 2021). A comparison of the AM hardware build times and cost projections was conducted to ensure the project requirements and schedule would be met (Gibson et al., 2021).

5. Software Selection

The team identified the software supplied by the AM hardware manufacturer to determine if commercial off-the-shelf software is required. The AM software that is commonly utilized includes the following:

1. Stereolithography (STL) editor and repair: AM editing software allows the user to repair errors and design edits to prepare the part for the AM build process (Gibson et. al., 2021).
2. Slicer and scan generator: Slicer software is built into the AM printer. External commercial slicer software is also available with dynamic features, such as extruder prioritizing and adaptive layer height (Gibson et al., 2021).
3. Process simulation: Process simulation analyzes deficiencies or potential problems with the design. It is a decision support feature that helps identify a build strategy (Gibson et al., 2021).
4. Support generation: Support generation identifies where supports are positioned based on the geometry of the product (Gibson et al., 2021).
5. Topology optimization: Topology optimization is an iterative process that enables material optimization. Structural optimization and multi-physics are types of topology optimization (Gibson et al., 2021).
6. Machine scheduling: Machine scheduling utilizes build time information to maximize scheduling and time utilization (Gibson et al., 2021).



7. AM process: AM utilizes layer-based manufacturing principles to construct 3D prototypes and end-use items. As indicated in Figure 27, the 3D product is developed from the 3D computer-aided design model. The 3D CAD model is converted to an STL file. A tessellation of triangles is generated, which represents the product boundaries (Gibson et al., 2021). The 3D printer reads the STL file as two-dimensional slices. The product specifications or build parameters are populated manually. The parameters pertain to the material energy, dimensions, and time requirements. Thus, the 3D printer builds each layer as a two-dimensional slice based on the 3D build parameters. The final steps involve the support removal, if utilized, and finishing processes. The AM process is outlined in Figure 26.

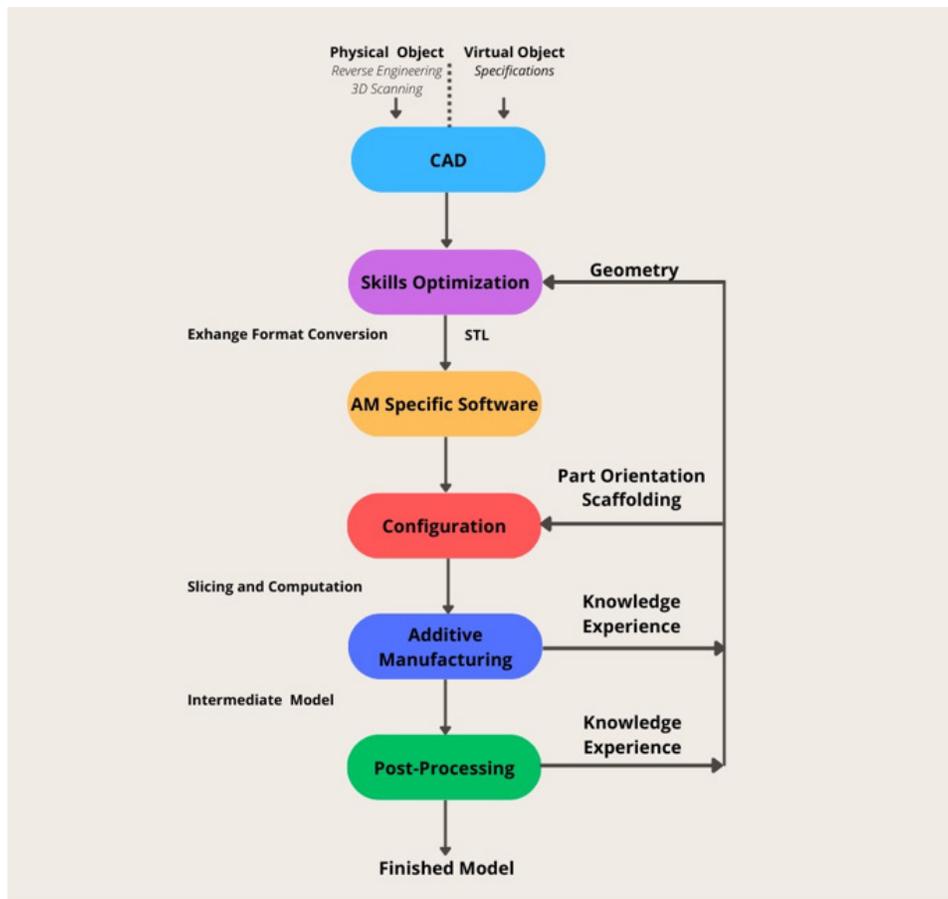


Figure 27. Additive Manufacturing Process. Adapted from Niaki and Nonino (2018).

1. Computer-aided design model: The external geometry of the product is defined in the software representation (Gibson et al., 2021).
2. Exchange format conversion: The AM software converts the computer-aided design data to the predominantly used file type, STL. The 3D printer translates the data into layers or slices of information, which are referred to as software slices (Niaki & Nonino, 2018). The dimensions derived from the computer-aided design model are used to calculate the software slices.
3. Skills optimization: Topology optimization is the focal point. The objective is to analyze geometry to determine the most efficient design, which optimizes the strength, weight reduction, and geometry and minimizes material waste (Niaki & Nonino, 2018).
4. AM-specific software: AM software functionality includes relaying instructions to the 3D printer, performing structural analysis and process simulations, and serving as a data management repository (Gibson et al., 2021).
5. Configuration: The STL file is transferred to the AM machine to evaluate the position, size, and orientation of the part (Gibson et al., 2021). File manipulation may be required to obtain the product requirements (Gibson et al., 2021). The setup of the AM machine, including the build parameters, is completed (Gibson et al., 2021).
6. AM: The build process is automated and requires minimal supervision to confirm the power, software, material levels, and issues (Gibson et al., 2021). The part must be removed from the AM platform with care.
7. Post-processing: The step involves the cleaning up, priming, painting, and removal of support structures, if applicable. The objective is to achieve the desired surface and texture, which may require heat treatment or final surface treatments (Gibson et al., 2021).



6. Quality Control Process

The team established a quality control process, as depicted in Figure 28. The steps outlined verify the integrity of the product. There are redundancies in place to ensure the product meets the quality standards outlined in the product specifications. The quality is monitored throughout the AM production life cycle. The production process is reinitiated if a concerning quality is identified at any time during the production process (Salmi, 2022). The team assessed the internal and external factors, which impact the part quality, as outlined in Figure 28 (Dietrich et al., 2019).

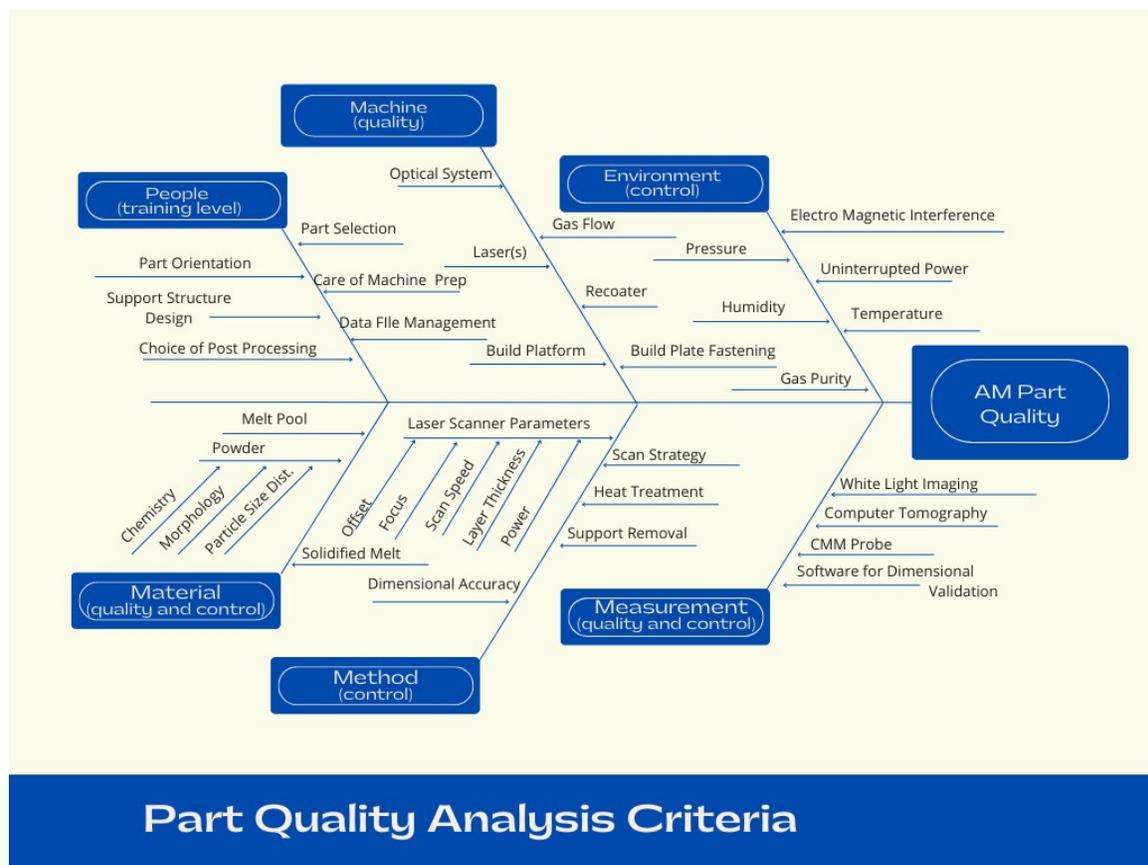


Figure 28. Part Quality Analysis Criteria. Adapted from Dietrich et al. (2019).

7. Direct Ink Write

DIW is a form of material extrusion. A controlled selective deposition of material is distributed in a controlled pattern based on the build parameters.

a. Formulation

The team developed an AM-compatible HES 5808 formulation. Identical composition, ingredients, and processing solvents were utilized to support the AM processing (Perry, 2022).

b. Hardware Selection and Development

The EMAM redesigned the Fisnar F9000N printer (Perry, 2022).

1. The Fisnar F9000N is a commercial-off-the-shelf gantry robot originally intended for in-line industrial automation for large paste dispensing of materials such as solder, lubricants, epoxy, and so on.
2. The machine's controller box was completely replaced with open-source AM hardware to allow for more precise tool pathing, adjustable dispense rate, in situ analysis, and the use of additional software, such as Duet3D/RepRap.
3. The extrusion head was completely redesigned to be powered by a DC motor to handle materials with heavy solid loadings, such as energetic materials.

c. Software

The Fisnar F9000N utilizes Duet3D/RepRap, which is the configuration software for the printer. A custom data intake form is also used to conduct the data collection, which relays data directly into the Postgres database. Postgres is a software tool to track 3D build information.



d. Quality Controls

An enclosure was designed to address the temperature and humidity in the printing environment, as illustrated in Figure 29.

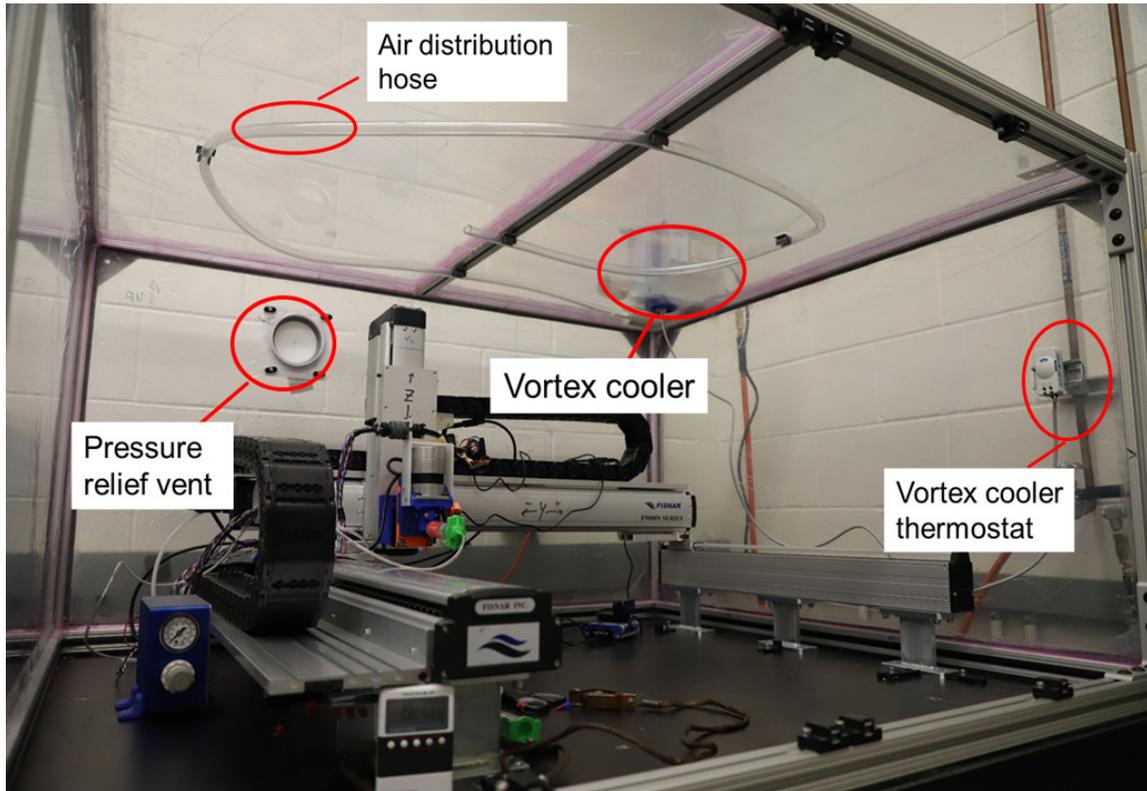


Figure 29. EMAM Enclosure. Source: Perry (2022).

e. Materials

The material is usually patterned through a nozzle, whose movement is controlled by software and parameters. The AM energetic feedstock process for the DIW is as follows:

1. Energetic feedstock is manufactured in a Resonant Acoustic Mixer with the considerations for the key parameters, mix homogeneity, solvent loadings, and packing of HES 5808 in the syringe without bubbles (Perry, 2022).

2. Energetic feedstock is loaded in syringes that were adapted to interface with the AM gantry as depicted in Figure 30 (Perry, 2022).
3. A pneumatic press pushes the energetic material out of the syringe and into an auger, which in turn can extrude the material through nozzles of 0.41, 0.25, and 0.20 mm in diameter.

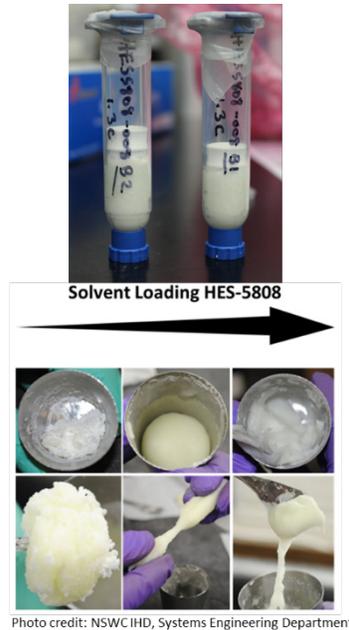


Figure 30. Solvent Loading. Source: Perry (2022).

f. Curing

Precision is a key advantage of AM, which significantly improves the reliability and consistency of the HES 5808 propellant grain. The AM product results in improvements to the ballistic output and product quality. AM is often utilized as a supplement to traditional manufacturing. In this case, the addition of printers and extrusion heads would increase the probability of the long-term potential. However, additional research is required to reduce the ultraviolet (UV) curing drying cycles.

g. Post-Processing

The team inserted needles to clean up the holes when required. Support drains and angles were also utilized, as shown in Figure 31.



Use of supports and drainage angles.

Figure 31. Post-Processing. Source: Minehan (2022).

8. HES 5808 Development Life Cycle

Figure 32 illustrates the progression or timeline of improvements achieved during the study. Smaller dimensions were achieved, as illustrated, at the end of the timeline.

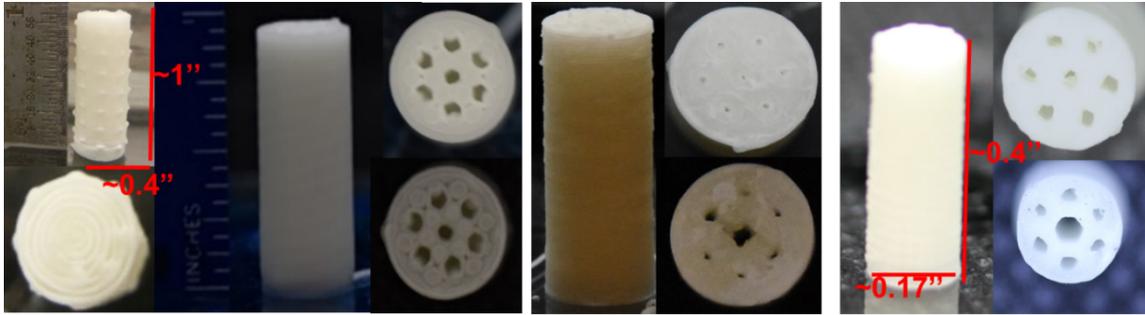


Figure 32. HES 5808 AM Development Life Cycle. Source: Perry (2022).

9. Digital Light Processing

DLP utilizes a light source or DLP projector to cure the layers of photopolymer (Niaki & Nonino, 2018)). The resin properties are cured from liquid to solid after each layer is deposited (Minehan, 2022).

a. Formulation

The UV curable feedstock is under investigation for viability as a material to fill the criteria of product needs. Based on the research findings, the DLP methodology is compatible with acrylic resins as explained in Figure 33. Acrylic is a viable material candidate because of its physical properties, such as its density.

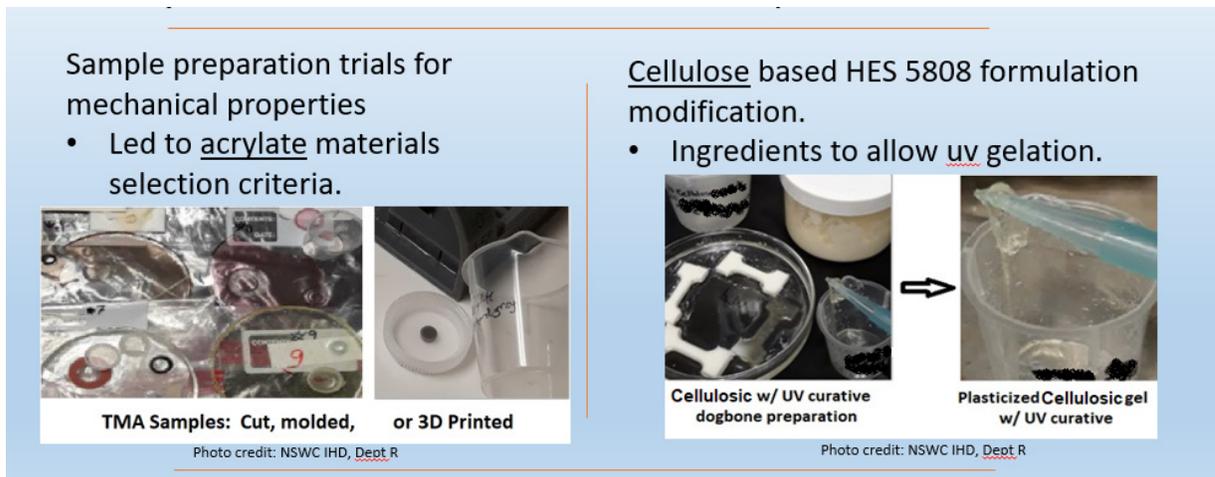


Figure 33. DLP Materials Research. Source: Minehan (2022).

b. Hardware Selection and Development

The B9Creations printer and modified projector simultaneously cures a full x-section layer of UV-sensitive resin (Minehan, 2022).

c. Software

DLP utilized software similar to DIW. The specific software information is not available.

d. Quality Controls

The team utilized the EMAM enclosure to regulate the printing environment.

e. Materials

The materials are under investigation.

f. Curing

DLP uses UV light to cure polymeric feedstock.

g. Post-Processing

A process similar to DIW is required.

(1) Cost Analysis

The cost information is not available. A projected decrease is expected because of the waste reduction and other efficiencies. As with most AM projects, the AM machine accounts for the highest percentage of the total costs as illustrated in Figure 34 (Kamara & Faggiani, 2021). The current average cost per unit for the HES 5808 is \$10.00. Generally, the part cost increases based on the complexity.

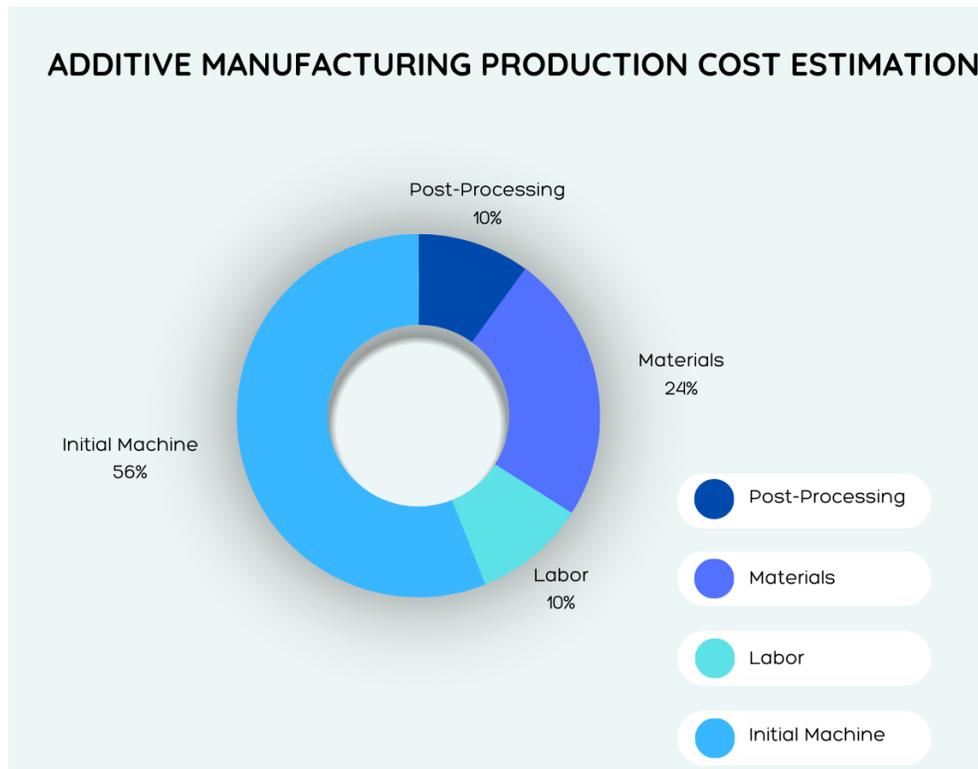


Figure 34. Additive Manufacturing Costs. Adapted from Kamara and Faggiani (2021).

(2) Supply Chain

The M91 cartridge supply chain would parallel the traditional manufacturing with HES 5808. Upon successful testing, NSWC IHD would be the only qualified AM manufacturer. The supply chain structure would be like the traditional manufacturing with HES 5808 as illustrated in Figure 35.



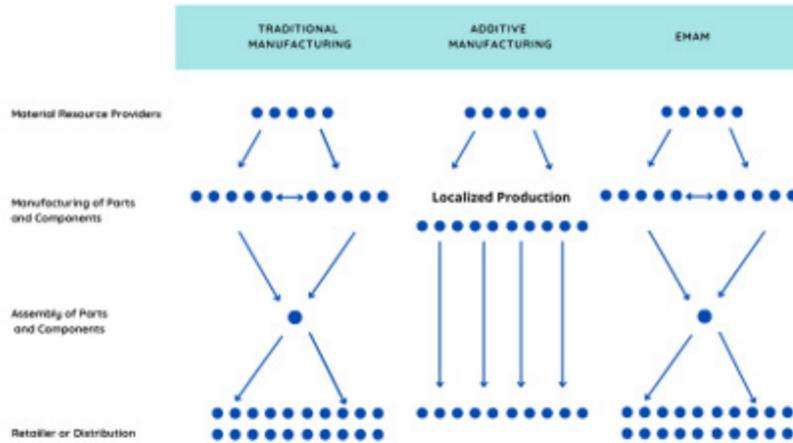


Figure 35. EMAM Supply and Logistics Framework. Adapted from Thomas and Gilbert (2014).

(3) IP Challenges

It was determined that NSWC IHD has IP rights to the HES 5808 formulation.

(4) Risk Assessment

The MRL and TRL assignments indicated in Table 7 are based on the development phase.

Table 7. MRL and TRL Risk Assessment

	Direct Ink Write	Digital Light Processing
MRL	4	4
TRL	4	4

F. PROJECT REVIEW PREPARATION

The EMAM team conducted an internal meeting to prepare for the project review. The CAD/PAD JPO distributed a list of agenda items: BTI, SWOT analysis, project schedule, and project constraints.



1. Barriers to Implementation

The BTI analysis, as illustrated in Table 8 is an exploratory cross-sectional evaluation of the DIW, DLP, and traditional manufacturing methodologies. A qualitative assessment of the technological, economic, business, and acquisition factors assist in identifying the R&D and implementation challenges. Predetermined factors are identified by the CAP authors: AM Technology, Formulation and Materials, Verification and Validation, Environmental, Economic, Operational, Acquisition/Procurement, Configuration Management, Supply and Logistics, and Business Strategy. The EMAM team applied rating assignments of 1–5, which highlights the facilitators versus barriers for each manufacturing method. The rating of 1 is a facilitator, while the rating of 5 is a barrier.

1: Exceeds Objectives

2: Meets Objectives

3: Below Objectives

4: Far Below Objectives

5: Under Development

a. *Hardware and Software Compatibility*

The DIW AM hardware, Fisnar F9000N, is compatible with the HES 5808 formulation. Although the DLP AM hardware, B9Creations, has the potential to manufacture a high-resolution product, the formulation concerns are unresolved. The DIW hardware required no deviation from the HES 5808 formulation.

Both the DIW and DLP analytic and decision support software tool have the potential to support the product specification requirements. The DIW software compatibility is a key factor in research advancements. These tools supported the topology and design optimization, which facilitated less waste and a reduction in anomalies. The DLP tools were less compatible and prohibited the development process.



b. Feasibility and Compatibility of Formulation and Materials

Per the BTI scores applied, the DIW and DLP methodologies are both feasible and compatible manufacturing solutions. The ability to meet the HES 5808 formulation specifications is evaluated using the feasibility criteria. The HES 5808 formulation did not require a modification to support the DIW manufacturing process. A formulation modification is required to support the DLP manufacturing process. The ability to perform the manufacturing process without deviating from the HES 5808 formulation indicates DIW is a more feasible solution.

The compatibility criteria assess the formulation and materials in conjunction with the AM technology. In terms of compatibility, both the DIW and DLP are compatible. However, additional research is required to identify material that is compatible with the DLP methodology. DIW can extrude the materials with viscosity considerations.

c. Reproducibility, Repeatability, and Reliability

The assessment of the key performance indicators—reproducibility, repeatability, and reliability—is derived from the quality assurance, testing, safety, and analysis criteria. Quality assurance is evaluated in terms of the ability to replicate the product dimensions, density, and composition. DIW, DLP, and traditional manufacturing can achieve the quality assurance requirements.

Testing to determine the viability of each manufacturing type is required to assess the cost-effectiveness in comparison to the project triple constraints. Viability testing was conducted for both DIW and traditional manufacturing. The testing is incomplete for DLP.

The safety assessment asserts that DIW, DLP, and traditional manufacturing follow the safety protocols. Additional safety measures, such as the encapsulation of fumes, are achievable with AM. The safety requirements are attainable for each methodology, but the AM enclosure limits the exposure of fumes.

The analysis is completed in a simulated environment when assessing the DIW, DLP, and traditional manufacturing. In situ analysis can be utilized throughout the AM manufacturing process to identify design and topology anomalies and corrective actions.



Postproduction simulated conditions, such as closed vessel testing, apply to both AM and traditional manufacturing.

The likelihood of the product's performance is ascertained through the evaluation of the key performance indicators: reproducibility, repeatability, and reliability. These indicators are measurements that are derived from the quality assurance, testing, safety, and analysis requirements and results. DIW is more likely to address the reproducibility, repeatability, and reliability concerns based on the BTI ratings.

d. Environmental Sustainability

AM fosters sustainable environmental practices by reducing energy consumption. A reduction in energy consumption is achieved through manufacturing processing time improvements, less fuel resource use, less floor space, less building maintenance, and drying time reductions. Each of these benefits equates to less energy consumption.

e. Economic Sustainability and Viability

The AM methodology can achieve the quality and performance objectives with considerations for cost-effectiveness and practicality. AM is more cost-effective in comparison to traditional manufacturing. Benefits such as floor space and processing time reductions are catalysts for the cost reductions. In addition, the economies of scale are not a significant economical factor due to the inherent flexibility of AM.

f. Operational

The AM methodology can support the manufacturing operations effectively. Factors such as economies of scale and human system integration will have minimal impact to productivity and operability. While the development of operation procedures, training, and workforce development are mitigating factors, minimal impact is expected based on the level of tasking.

g. Acquisition and Procurement Adaptability

The comprehensive benefits of AM are supportive of streamlined acquisition and procurement processes.



h. Configuration Management, Supply Chain, and Logistics

Upon the successful testing of the AM HES 5808 product, NSWC IHD will be the only qualified HES 5808 AM manufacturer. The acquisition and procurement would remain like traditional manufacturing. However, there is potential to streamline the process should NSWC IHD assume the role of manufacturing the M91 cartridge as well as the HES 5808.

The analysis findings of the technological, economic, business, and acquisition factors are provided in Table 8.



Table 8. Barriers to Implementation

Factor	Subfactor	Area of Analysis	DIW	DLP	Trd	Evidence	Notes
AM Technology	Hardware Compatibility Ability to support the manufacturability of propellant	Product manufactured within physical and chemical properties	2	1		Ease of application to the product specification requirements dictated this assessment. The DLP can provide higher resolution of the product.	Based only on the research performed, the DIW AM methodology best supported the manufacturing of propellant.
	Software Compatibility Ability to support an optimized design with considerations for design, shape, and topology optimization	Analytic and decision support tools streamlined the design process	2	3		Ease of application to the product specification requirements.	Some same, and different software types were utilized as appropriate to the two methodologies. Data in correlation to specifications were analyzed.
Formulation and Materials	Feasibility Ability to formulate with no or minor modifications	AM formulation developed within the specifications	1	2		The DIW operates using the same formulation as the traditional manufacture, whereas the DLP methodology required a formulation modification.	
	Compatibility Ability to support the manufacturability in relation to the AM technology and methodology.	AM formulation is compatible with the AM technology.	1	1		The DIW compatibility was assessment based on the ability to extrude with considerations for viscosity. DLP requires further research to identify a compatible material.	Studied variations in viscosity during research to settle on convenient printing features such as material flow control.
Verification and Validation	Reproducibility, Repeatability, and Reliability Ability to deliver a comparable or higher quality product based on the performance and safety requirements	Quality Assurance Ability to meet or exceed the quality assurance parameters	1	1	1	Product material specifications such as dimensions, density, and composition are used as quality assurance parameters.	
		Testing Ability to meet the testing parameters	1	3	1	DLP was not researched to the point of viability testing.	
		Safety Ability to meet or exceed the safety parameters	1	1	2	While traditional manufacture meets safety protocol, AM allows for better environmental control and encapsulation of fumes.	
		Analysis Ability to monitor and assess the quality and performance throughout the AM manufacturing	3	3	3	Performance in simulated conditions is ultimately used to monitor or analyze the quality and performance	



DIW	Direct Ink Write
DLP	Digital Light Processing
Trd	Traditional



Table 8 (cont.) Barriers to Implementation

Factor	Subfactor	Area of Analysis	DIW	DLP	Trd	Evidence	Notes
Environmental	Sustainability Ability to reduce the resource consumption	Reduction in materials waste Reduction in energy consumption Reduction in hazardous waste	1	1	4	Overall, a reduction is seen in processing time, which directly reduces energy output and also reduces fossil fuel resource use. Using less floor space, AM will require less building maintenance, hence less energy consumption. Less hazardous waste was used by using a modified solvent selection. Product drying time will be greatly reduced, hence even less energy use.	
Economic	Sustainability Viability Ability to achieve the quality and performance objectives in relation to the cost-effectiveness and practicality	Cost Versus Benefit Increased cost outweighs the constraints Equivalent cost and increased benefits Lower cost and increased benefits Economies of Scale Ability to achieve cost-effectiveness as a low volume scale product	1	1	4	AM is more cost-effective. AM can be completed over much less floor space. AM processes can be completed in much less time (with less cleanup).	
Operational	Productivity Operability Ability to support operations effectively in terms of the projected economies of scale with considerations for human system integration	Processes Development of operations procedures Safety and handling Training/Workforce Development Development of training programs and procedures Hiring, training, and retention of AM engineers and other support personnel	1	1	3	While AM Training/Workforce Development requirement is higher, the educational requirement will not exceed the work at hand.	Predict that a 3 ranking for traditional manufacturing will migrate to a 4.
Acquisition/ Procurement	Adaptability Ability to employ strategic agreements in relation to cost-effectiveness; competitive advantage	Processes Development of contracting strategy procedures	1	1	3	Less processing time for AM will provide a distinct advantage.	Predict that a 3 ranking for traditional manufacturing will migrate to a 4.
Configuration Management, Supply Chain, and Logistics	Traceability Releasability Resiliency Sustainability Ability to support a streamlined process supportive of the AM technology	Processes Development of streamlined processes to support warfighter requirements	2	2	2		
Business Strategy	Feasibility Sustainability Supportive of sponsor's requirements, economic objectives, and operational effectiveness	Strategic Objectives Development of strategy that is economically feasible and supports product improvement	2	3		A more precise manufacturing process produces a more consistent product. AM facilitates the delivery of higher quality product to the customer.	The ranking chosen is overall. Precision of manufacturing on different areas affects the product in different ways. To say, "AM facilitates the delivery of higher quality product to the customer," is a comparison to traditional manufacturing.



2. Strengths, Weaknesses, Opportunities, and Threats Analysis

An analysis of the EMAM competitive advantage is depicted in Figure 36. An evaluation of the internal and external strengths, weaknesses, opportunities, and threats (SWOT) was conducted. SWOT analysis is an effective strategic tool that can be used to evaluate business strategies. The SWOT assessment of strategic areas aids in the identification of business opportunities, efficiencies, and potential threats.

a. Strengths

Strengths refer to “the internal elements of an organization that facilitate reaching its goals, while weaknesses are those internal elements that interfere with organizational success.” (Aldehayyat & Anchor, 2008; Fleisher & Bensoussan, 2003; Lee & Lin, 2008; Shrestha et al., 2004). Contrary to most explosive manufacturing technology methods, the HES 5808 does not utilize rare earth elements. Environmental sustainability is another strength of the AM project. The manufacturing type results in less energy consumption, which translates to a reduction in volatile organic compounds and less waste. In addition, software optimization fosters design, shape, and topology optimization.

b. Weaknesses

The availability of industry-wide standards and practices will evolve as AM is widely adopted. Standards are under development by organizations, such as the International Organization for Standardization and American Society for Testing and Materials. The lack of a standardized protocol, scale-up procedures, and benchmark characterization tests are weaknesses that affect not only the EMAM project but AM projects in general. An analysis of the HES 5808 supply and logistics framework indicates that the HES 5808 is a critical component of the aircrew escape system and must be manufactured in a controlled environment. The organizational culture was deemed a weakness in this assessment. AM is widely accepted in the commercial industry but is a novel practice in the DOD due to the change-resistant culture.



c. Opportunities

Opportunities pertain to the external prospects to promote growth and obtain objectives. Analysis is often utilized to address capability gaps and initiate new activities. The AM manufacturing process can promote a sustainable product and green initiatives and offers incentive to support workforce development and retention.

d. Threats

Although AM technology is expanding in the DOD, it is considered novel depending on the product type, such as propellant. Managing the expectations of the stakeholders while meeting the AM project requirements is a primary concern. Often, technological advancements outpace the organizational culture, which may lead to the valley of death, which pertains to the potential lack of support and funding from the stakeholders.

The EMAM team briefed the SWOT analysis outlined in Figure 36. A SWOT analysis is a formal way to analyze the strength, weakness, opportunities, and threats of an organization.

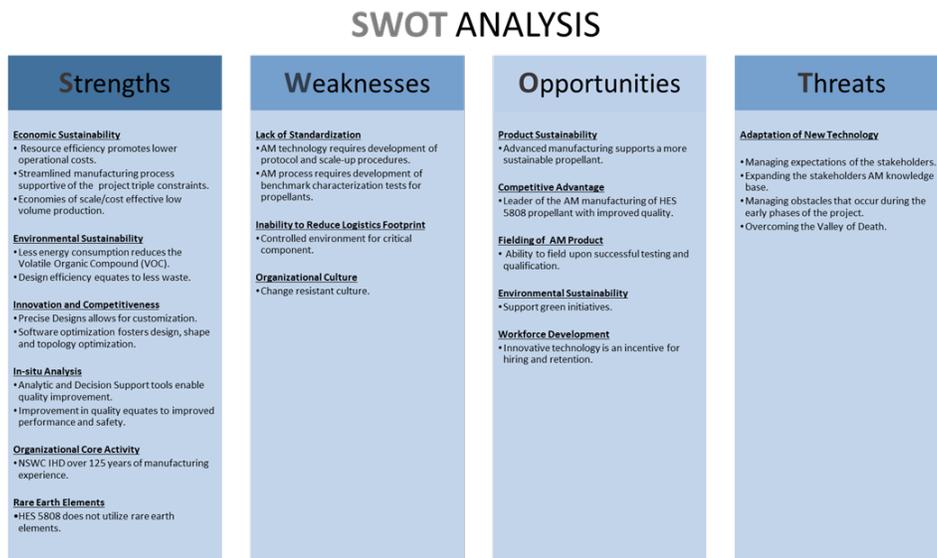


Figure 36. EMAM SWOT Analysis



While AM is a viable solution because of the innate flexibility, which equates to design and topology optimization, traditional manufacturing is a core activity of NSWC IHD, as evidenced by the 125 years of experience. The organization also has the capability to transfer this knowledge in support of the EMAM project.

The benefits and constraints of traditional manufacturing and AM vary depending on the project objective, manufacturing methodology, and project constraints. However, AM benefits typically pertain to economic sustainability, environmental sustainability, innovation, and competitiveness. The technological advantages, such as in situ analysis, foster design optimization.

AM utilizes less resources, which translates to economic sustainability. Lower operational costs are achieved through less power consumption and human resources, while the start-up expenses account for the largest percentage of the total ownership cost. The flexibility of AM allows for proactive and reactive planning, which makes the economies of scale less relevant.

The EMAM project has the potential to streamline the HES 5808 manufacturing. The inherent AM attribute, flexibility, correlates to a more agile AM project. The project triple constraints are positively impacted, which is attained through the design and manufacturing flexibility. Design efficiency and customization are supportive of product improvements with minimal impact to the schedule.

The AM of propellant is novel to the DOD. The lack of standardization, protocols, benchmark characterization tests, and scale-up procedures are obstacles for the EMAM project. Additional R&D and testing will support the development of standard practices. The novelty of the manufacturing type will also impact the decision-making authority's perspective. The perceived risk associated with the AM of propellant and change-resistance culture will significantly impact the decision to establish a formal program. The inability to reduce the logistics footprint is also considered a weakness and a decision-making variable.

AM presents opportunities, such as product sustainability, competitive advantage, fielding of AM products, environmental sustainability, and workforce development. The



in situ analysis allows for mid-cycle design modifications and supports flexibility, agility, and sustainability. The result is improved product quality, and the organization will have a competitive advantage as the only AM-qualified HES 5808 manufacturer. The technological breakthrough is supportive of workforce development initiatives, which supports hiring and retention.

Per the SWOT analysis, the overall DIW manufacturing benefits outweigh the cost increase incurred during the initial startup. The improvements in quality equate to product sustainability, cost sustainability, and efficiency.

3. EMAM Project and Acquisition Milestones

The EMAM team developed an acquisition schedule with the understanding that NSWC IHD will be the sole source AM manufacturer. The major acquisition milestones are highlighted in Figure 37. Energetic material qualification is a key milestone. The material qualification proceeds the cartridge evaluation process. The design reviews will occur if the cartridge evaluation process is successful.

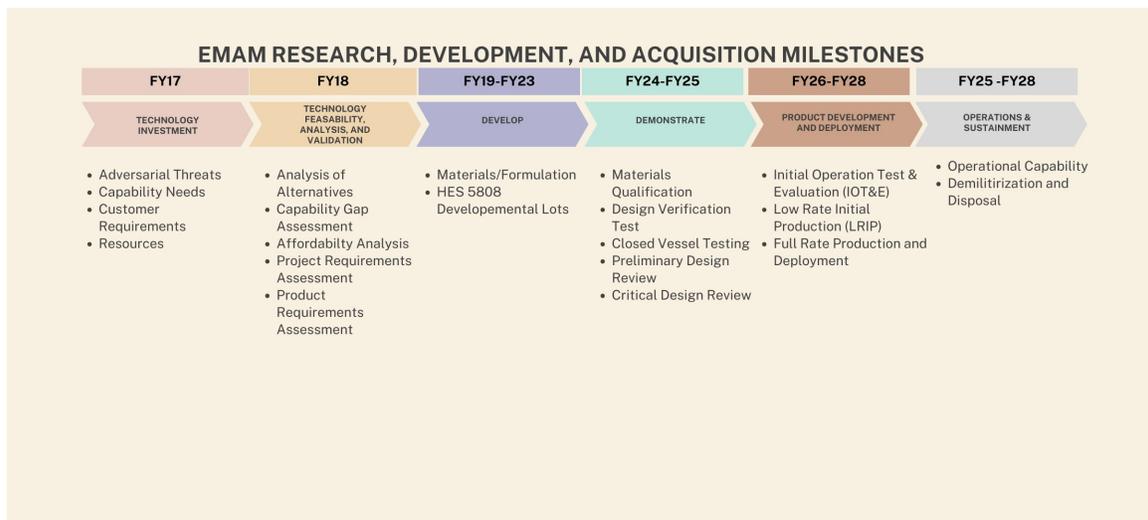


Figure 37. EMAM Milestones



4. Dilemma

The CAD/PAD JPO must determine the best path forward that addresses the quality, IP, and MIB concerns. There is an established acquisition program for traditional manufacturing. While the flexibility of AM supports the optimization of the design and manufacturing process, the testing and qualification to support a formal acquisition is incomplete. The JPO must determine the trade-offs and devise a strategy to address the change-resistant culture.



V. CASE STUDY ANALYSIS

The EMAM case study addresses the inflexibility of the HES 5808 traditional manufacturing. The traditional method results in product imperfections and waste. The innate flexibility of the AM methodology and projects not only addresses the waste and imperfections but has the potential to address the IP, logistics, and supply chain concerns. The limited number of consumers is a root cause of the logistics and supply chain issues in the past. It was not economically feasible for Alliant Techsystems to manufacture the product or conduct the R&D to resolve the quality issues. These issues are attributed to the financial constraints and change resistant culture. As a result, NSWC IHD assumed the role of manufacturing the HES 5808 product. Currently, NSWC is a qualified second source vendor.

The HES 5808 traditional manufacturing research explored the formulations and ratios, and assessed the internal and external quality. The low solids fill formulation resulted in improved internal and external quality, while the high solids fill formulation only improved internally or externally; improvements were not achieved both internally and externally.

The secondary traditional R&D effort, Proof of Principle Study to Replace RDX in LOVA-Style Propellant Formulations, investigates an HES 5808 alternative. An increased burn rate was achieved with the nano-aluminum formulation, while there was little effect on the burn rate with the micron-sized aluminum and oxidizer formulation. Both nano-aluminum and micron-sized aluminum and oxidizer formulations met the readiness criteria for demonstration testing based on the performance. The burn rate and simulated ballistic performance of the replacement propellant were within ranges similar to HES 5808.

The limited number of qualified vendors and consumer base are concerns. Per the case study research, the government is the primary HES 5808 consumer. Alliant Techsystems was unable to sustain the financial burden, which forced the company to suspend the HES 5808 manufacturing. In a case such as this, a cost-plus incentive contract



is a potentially viable option. This contract type will fund the manufacturing and the R&D to address the quality concerns.

The EMAM study focuses on the AM of the HES 5808 propellant. An analysis of the DIW and DLP methodologies was conducted. A DIW-compatible HES 5808 formulation with identical composition, ingredients, and processing solvents was developed. The DIW product results in less waste and anomalies. A compatible formulation was not identified for the secondary AM methodology, DLP. The materials are under investigation.

The Program Management Institute's (PMI's) project triple constraints apply to AM projects, as indicated by the case study research. As illustrated in Figure 38, a secondary layer of project constraints is applicable to the EMAM project. The primary constraints outlined by the PMI are time, scope, and cost (Baratta, 2006). The secondary layer assesses the project agility, sustainability, and flexibility (Niaki & Nonino, 2018). Flexibility is the most recognizable attribute of AM. The inherent flexibility of advanced manufacturing, specifically AM, is the driver for its widespread use in the commercial industry and upsurge in the DOD.

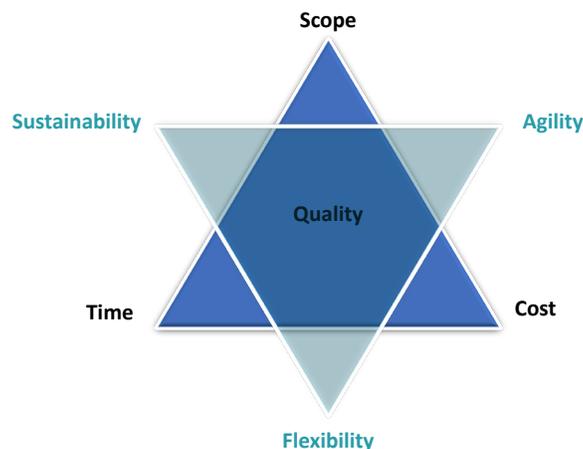


Figure 38. AM Project Constraints. Adapted from Baratta (2006), Niaki and Nonino (2018).

Flexibility refers to the ability to enable change with consideration for both the internal and external impacts (Eyers et al., 2018). The research tools, BTI and SWOT analysis, help in the assessment of the flexibility of the AM methodologies, DIW and DLP. In addition, the internal and external benefits and the constraints of the EMAM project were analyzed.

Both the internal and external AM project impacts are derived from the AM methodology and the 3D printer utilized. The external aspect addresses the collective benefits of AM, such as design, schedule, and cost flexibility. These collective benefits are evidenced by the ability to manufacture on demand, produce complex parts, and maintain design flexibility. The secondary project constraints are flexibility, sustainability, and agility and are evaluated throughout the project life cycle.

In terms of flexibility, the design, cost, and schedule latitude has rendered the economies of scale irrelevant. Sustainability pertains to product consistency, cost stability, environmental factors, and business models. Furthermore, agility refers to the ability to increase or decrease production as needed, which correlates to supply chain and logistics resiliency. The internal impacts, or level of flexibility, are determined by the following variables: material, software capability, AM methodology, 3D printer, and the internal processes employed. Furthermore, the internal variables are considerations to achieve the performance objectives. The level of flexibility is predetermined during the project identification and planning phases. The internal variables are elucidated through the assessment of the project objectives and triple constraints throughout the project life cycle. Therefore, the level of flexibility is directly related to the selection of the AM design and manufacturing type.

The evolution of AM technology is a determinant when assessing the viability of the EMAM project. The progression of AM technology or printer capability impacts the project scope and limitations. A thorough analysis of the AM technology was conducted to support the continual DIW and DLP AM development.

As with traditional manufacturing, the AM project risk is lessened through quality assurance methods. Quality assurance measures the efficacy of the internal variables to



validate the precision or quality. The measurements are derived from analysis, testing, and validation, which are interpreted as repeatability, reproducibility, independent quality, and non-guarantee-able quality. The components' repeatability and reproducibility are often used interchangeably. Per the American Society for Testing and Materials E117, the differentiating factor is repeatability, which does not account for the variances in the operators, environmental conditions, locations, and equipment. Both components are relevant to the AM design and byproducts of the internal variables, which determine the level of flexibility.

AM technology has evolved, reducing the risk associated with independent quality. Although the improvements of the AM platforms did not eliminate the opportunity for human error, the probability is reduced significantly. The platforms reduced the number of parameters available to the operator, thereby reducing the risk of human error. The incorporation of software optimization in the platform also lessens the risk. Environmental conditions, such as temperature and humidity, also influence the independent quality. In the case of the EMAM project, this risk is mitigated by 3D printing within an enclosure to regulate temperature settings.

The EMAM research indicates that AM is a viable candidate to support propellant manufacturing. The innate flexibility results in design efficiency, which results in fewer anomalies. It also addresses environmental sustainability through less energy consumption, which reduces volatile organic compounds.

A. DECISION MATRIX

A rating scale of 1–4, with 1 being best and 4 being worst, was utilized. The HES 5808 traditional manufacturing process is established; therefore, there is less risk associated. In addition, the acquisition program, including the contracts with vendors, is well-established. There are, however, quality issues with the traditional manufacturing process. The AM startup costs and novelty of propellant manufacturing are both deterrents, which equate to a higher risk level. Traditional manufacturing is the best option based on the criteria, which is provided in Table 9.



Table 9. HES 5808 Propellant Decision Matrix

	Traditional	Direct Ink Write (DIW AM)	Direct Light Processing (DLP AM)	Replace RDX in LOVA-Style Propellant (Traditional)
Cost	1	3	4	2
Schedule	1	2	3	4
Performance	2	1	3	4
Risk	1	3	3	3
MRL	1	3	3	3
TRL	1	3	3	3
BTI	3	1	2	4
SWOT	2	1	3	4
Quality	2	1	3	4
Reliability	2	1	3	4
Maintainability	1	2	4	3
Availability	1.5	1.5	3	4
Operability	1	2	4	3
TOTAL	19.5	24.5	41	45

Rating scale is 1–4, with 1 being best and 4 being worst.

B. SENSITIVITY ANALYSIS

The key performance indicators and rating methods outlined in Table 10 were utilized to complete the sensitivity analysis.

Table 10. Key Performance Indicators and Ratings Definitions

Criteria	Definition
<ul style="list-style-type: none"> For each criteria a value is given, with 1 being best in that criteria and 4 being worst. If two options are tied in ranking, take the average for the score. For example, if Options 1 and 2 are best in a criterion, each receives a 1.5 score. 	
Cost	A project triple constraint that measures the project budget.
Schedule	A project triple constraint that measures the milestones and project timeline.
Performance	A key performance indicator that measures the product performance with respect to the specifications.
Risk	A measurement that indicates the probability and likelihood of an event or consequence.
Manufacturing Readiness Level	A measurement of the manufacturing and quality risk level throughout the development.



Criteria	Definition
<ul style="list-style-type: none"> For each criteria a value is given, with 1 being best in that criteria and 4 being worst. If two options are tied in ranking, take the average for the score. For example, if Options 1 and 2 are best in a criterion, each receives a 1.5 score. 	
Technology Readiness Level	A measurement of the technology maturity.
Barriers to Implementation	An assessment of the obstacles that may prohibit the completion of a task or project.
Strengths, Weaknesses, Opportunities, and Threats	An assessment of the competitiveness to support strategic planning.
Quality	A key performance indicator that assesses the product or system based on the requirements and specifications.
Reliability	A key performance indicator that measures functionality based on requirements and specifications.
Maintainability	A key performance indicator that measures the ability to support/service a product/item based on the requirements and specifications.
Availability	A key performance indicator that measures the system failures and ease of the materials procurement.
Operability	A key performance indicator that measures the system functionality in an operational environment.

An assessment of the key performance indicators—BTI, TRL, MRL, and risk ratings—concludes that DIW is a viable solution. Each of the variables were weighted to account for the project priorities. Disruptive technology, such as AM, supports the strategic prioritization of inventory levels. AM is a supplementary manufacturing methodology, which is supportive of the NSWC IHD SCR initiatives. Furthermore, the EMAM study is the predecessor for future AM initiatives at NSWC IHD. While self-sustainability is an objective for the nation, it is equally important to NSWC IHD. The R&D and establishing a formalized acquisition program will further support the technological core competencies, as one of the Navy’s only arsenals. The assessment results are provided in Table 11.



Table 11. HES 5808 Sensitivity Analysis

Options	Weight	Traditional	Direct Ink Write (DIW AM)	Direct Light Processing (DLP AM)	Replace RDX in LOVA-Style Propellant (Traditional)
Cost	5	1 (5)	3 (15)	4 (20)	2 (10)
Schedule	5	1 (5)	2 (10)	3 (15)	4 (20)
Performance	5	2 (10)	1(5)	3 (15)	4 (20)
Risk	5	1 (5)	3 (15)	3 (15)	3 (15)
MRL	5	1 (5)	3 (15)	3 (15)	3 (15)
TRL	5	1 (5)	3 (15)	3 (15)	3 (15)
BTI	30	3 (90)	1 (30)	2 (60)	4 (120)
SWOT	15	2 (30)	1 (15)	3 (45)	4 (60)
Quality	5	2 (10)	1 (5)	3 (15)	4 (20)
Reliability	5	2 (10)	1 (5)	3 (15)	4 (20)
Maintainability	5	1 (5)	2(10)	4 (20)	3 (15)
Availability	5	1.5 (7.5)	1.5 (7.5)	3 (15)	4 (20)
Operability	5	1 (5)	2 (10)	4 (20)	3 (15)
TOTAL		192.5	157.5	285	365



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VI. SUMMARY

A key determinant of the conclusion was the HES 5808 compatibility with the AM methodology, DIW, with little or no deviation to the formulation. The evolution of the AM process resulted in quality improvements. As Perry (2022) affirmed, there were fewer anomalies with the HES 5808 solid propellant manufactured using the DIW methods. The method was demonstrated in a lab environment. Presumably, the AM method and processes established will ensure the results are reproducible in a test and operational environment.

The case study research indicates that AM is supportive of the DIB restoration and warfighter's mission readiness. The viability of the DIW methods is evidenced by the quality improvements and potential supply chain efficiencies. There is a high risk of supply disruptions because of the limited HES 5808 manufacturers. The incorporation of a supplementary manufacturing method lessens the risk of supply disruption. A strategic mechanism, such as AM, can support both proactive and reactive manufacturing strategies. The formalization of the DIW acquisition program will support the DOD and NSWC IHD strategic initiatives by promoting SCR.

A. CONCLUSIONS

The inefficiencies in the U.S. supply chain framework are a consequence of the waning U.S. MIB. Consequently, a weakened national security is an implication of import dependency. Supply chain disruptions are an intractable problem within the DOD and commercial industry, as evidenced during the COVID-19 pandemic and Ukrainian war. The primary objective of the supply change infrastructure is to enable resiliency in normal operations and heightened crises. However, the current infrastructure is resource-challenged and lacks agility. The current system is overly reliant on imports, which exposes the United States to vulnerabilities and sustainability challenges. Furthermore, the current JIT manufacturing model is incapable of supporting heightened crises. The employment of the DIW AM technology and processes fosters design flexibility, promotes efficiency, and facilitates redundancy and cost-effectiveness to enable the DOD competitive advantage



and military readiness (Naghshineh & Carvalho, 2020). Furthermore, the disruptive technology translates to SCR, which strengthens the DIB. AM is not bound by the economies of scale; therefore, it is supportive of the strategic prioritization of inventory levels, with the potential to reduce the logistics footprint. A strategic mechanism such as AM can supplement the global supply chain in conjunction with a streamlined acquisition process. In terms of the DIW method, the case study research indicates that a similar supply and logistics infrastructure will continue. The AM process could perform as the HES 5808 primary or secondary source.

However, the success of the DIW method is not without barriers. Constraints, such as the lack of AM standardization, impact the ability to repeat and reproduce the product. An additional key barrier is the inability to reduce the logistics footprint. A controlled manufacturing environment is required to produce critical components of the aircrew escape system. In addition, AM is widely accepted in the commercial industry but is a novel practice in the DOD due to the change-resistant culture.

B. RECOMMENDATIONS

The case study research indicates that DIW is a viable solution as indicated in Table 11, but a cost–benefit analysis is recommended to confirm the economic benefits or constraints. The initial capital investment incurred will not outweigh the long-term potential cost savings. The cost–benefit analysis results will also support the DIW acquisition program planning. The recommendation is to continue with traditional manufacturing until the DIW completes the demonstration and meets the requirements for initial production. Upon the successful completion of the DVT and material qualification, the CAD/PAD JPO should proceed with a formalized acquisition program.



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