# WRT-1052

# DIGITAL ENGINEERING TRANSFORMATION AT JPEO-CBRND

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## EXECUTIVE SUMMARY

This research effort extended previous work to identify the requirements of JPEO-CBRND regarding Digital Engineering Transformation in an Integrated Layered Defense (ILD) context. In particular, the research addressed avenues for JPEO to evaluate their complete portfolio at the enterprise level in order to execute appropriate acquisition decision-making. This research was conducted in two phases. During both phases, the researchers met regularly with the sponsor to continuously discover and address their needs.

In the first phase, the researchers developed an Agent-Based Model (ABM) to simulate a JPEO mission thread related to unmounted reconnaissance and decontamination of a chemically contaminated site. Input to the ABM came from a Model-Based Systems Engineering (MBSE) representation of the JPEO mission thread. The goal of this phase was to increase the researchers' familiarity with operational procedures at JPEO and to provide a use case to simulate multiple scenarios and support the identification of the best portfolio of technologies to execute a set of missions.

In the second phase, the researchers focused on Advanced Manufacturing, in particular Additive Manufacturing (AM). Currently, there is an army policy directing the consideration and use of Advanced Manufacturing in acquisition activities, as well as an Implementation Guidance from the Assistant Secretary of the Army for Acquisition, Logistics and Technology (ASA(ALT)). AM is a field that JPEO has not yet deeply considered. However, JPEO recognizes as a technology that can greatly benefit the organization. In order to include considerations about AM over the entire enterprise portfolio, JPEO must accomplish two functions. First, they must identify which capabilities and technologies in the JPEO portfolio are suitable to be implemented with AM techniques. Second, they must determine how to decide whether AM should be considered together with, or in lieu of, traditional subtractive manufacturing. These two functions became the subject of the second phase of the effort. To address these needs, the researchers proposed both SoS methodologies to analyze stakeholders and requirements at the enterprise level and key points based on use cases from the state-of-the-art in industry, which is useful for AM-specific Cost-Benefit Analysis for acquisition. This research, leveraging previous work both from SERC (SoS methodologies, previous work with JPEO, analysis of AM technologies) and from other research (ABM, literature review of AM state-of-the-art in the industry), resulted in a set of recommendations and lessons learned to guide future effort of JPEO in implementing Digital Engineering (DE) to address an analysis of the enterprise-level technological portfolio.

## BACKGROUND AND RESEARCH OBJECTIVES

The Directorate of Integration of the Joint Program Executive Office (JPEO) for Chemical, Biological, Radiological and Nuclear Defense (CBRND) currently has two top priorities which are applicable to SERC research. First, JPEO is continuing the effort to establish digital engineering across the whole spectrum of missions, technologies, and systems overseen by the Office. Second, JPEO is beginning to implement System-of-Systems (SoS) engineering, including building

SoS architectures and SoS modeling focused on integration. Furthermore, a new concept, called Integrated Layered Defense (ILD), is being developed by the CBRN community to holistically look at the CBRN SoS ecosystem and assess technical capability and trade-space between CBRN sensors, protection, and medical equipment. Within this context, JPEO is also addressing various directives that mandate the various services to consider Advanced Manufacturing, and in particular Additive Manufacturing (AM), in the acquisition process of technologies and components.

Following the SERC operational principles of conducting innovative, high-impact research and translating proof-of-principle prototypes into practical application, the team initially focused on the development of a simple Agent-Based Model (ABM) to simulate and analyze some of the JPEO procedures which are used to inform the acquisition and procurement process; in the second part of the research effort, the team specifically addressed AM and assessed the requirements which will allow JPEO to become ready to include AM technologies in the Cost-Benefit Analysis (CBA) process for acquisition.

## 1.1 RESEARCH NEEDED

Building upon previous work in WRT-1014, the WRT-1052 research performed the initial steps to support the Joint Program Executive Office for Chemical, Biological, Radiological and Nuclear Defense's (JPEO-CBRND) adoption of digital engineering (DE) into its acquisitions processes. JPEO-CBRND is currently modernizing the way it engineers CBRN systems and is looking at new techniques, methodologies, and tools to perform system of systems (SoS) engineering and integration on its portfolio. In particular, JPEO-CBRND identified the need to perform research that applies SoS engineering, Model Based Systems Engineering (MBSE) practices, in order to analyze the portfolio at the enterprise level and to support ILD. The research also explored SoS analysis to identify the needs of JPEO in the ILD context and investigated the steps necessary for JPEO to be ready to assess the inclusion of Additive Manufacturing (AM) and technology prioritization over the whole technological portfolio of JPEO, that is, at the enterprise level.

- The researchers shall acquire the foundational understanding of the current needs of JPEO-CBRND in Digital Engineering and in SoS engineering, with particular focus on integration and interfaces.
- The researchers conducted bi-weekly meetings with JPEO-CBRND to understand their needs, the current operational context, and requirements for MBSE and SoSE in Integrated Layered Defense.
- The researchers assessed the use of MBSE artifacts to inform the simulation of various scenarios, with the two-fold objective of identifying best practices in JPEO mission threads and supporting the decision-making of appropriate technological requirements
- The researchers translated knowledge about AM from specific case studies into a framework for enterprise-level evaluation of AM technologies and of requirements for JPEO to be able to perform appropriate Cost-Benefit Analysis in the AM domain.

- The researchers identified recommended managerial and technical approaches to expand this research into future efforts and to implement.

## WRT-1052 Achievements

We conducted research in two phases as follows:

- Phase 1: Development of An Agent-Based Model of JPEO Mission Thread
- Phase 2: Additive Manufacturing and JPEO Enterprise-Level Portfolio

### 1.2 Phase 1: Development of an Agent-Based Model of JPEO mission thread

In support of the effort to advance Integrated Layered Defense (ILD) capabilities, our research started with studying the field operations JPEO supports. Modeling JPEO-CBRND's relevant efforts involved weeks of developing paper models and asking clarifying questions about properties and functions of interest to the system, such as CBRND military org structures, order of operations/time required, nature of threats, etc. This modeling was developed to test variable mission scenarios so communication/logistics bottlenecks or other weaknesses to ILD could be identified and strengthened.

The method of modeling selected for this first portion of the research was agent-based modeling (ABM) for several reasons:

- Appropriate scope for all relevant structures (Brigade combat teams, hazard response companies, recon platoons, etc.) can be modeled (focusing just on the functions of interest and amount of detail required).
    - Example: the mechanics of a recon platoon surveying every detail of an area is not necessary (or prudent) for this modeling/analysis. Simulating the general time and order of events for a division to respond to multiple threats at a time can facilitate useful conclusions around overall CBRND threat neutralization.
- A recent SERC project (REALM) successfully developed an ABM, so development time could be accelerated on this project as some structures were available to be adapted.
- Agent-based models typically run quickly, allowing many simulations and rapid testing of policy changes.

Between January and March 2022, JPEO personnel provided needed details about mission operations, military structure, sample mission threads, equipment capabilities, etc., enabling a better understanding of JPEO-CBRND's needs and field operations. Some of the most relevant information about the field operations model is included in the paper model in Figure 1.

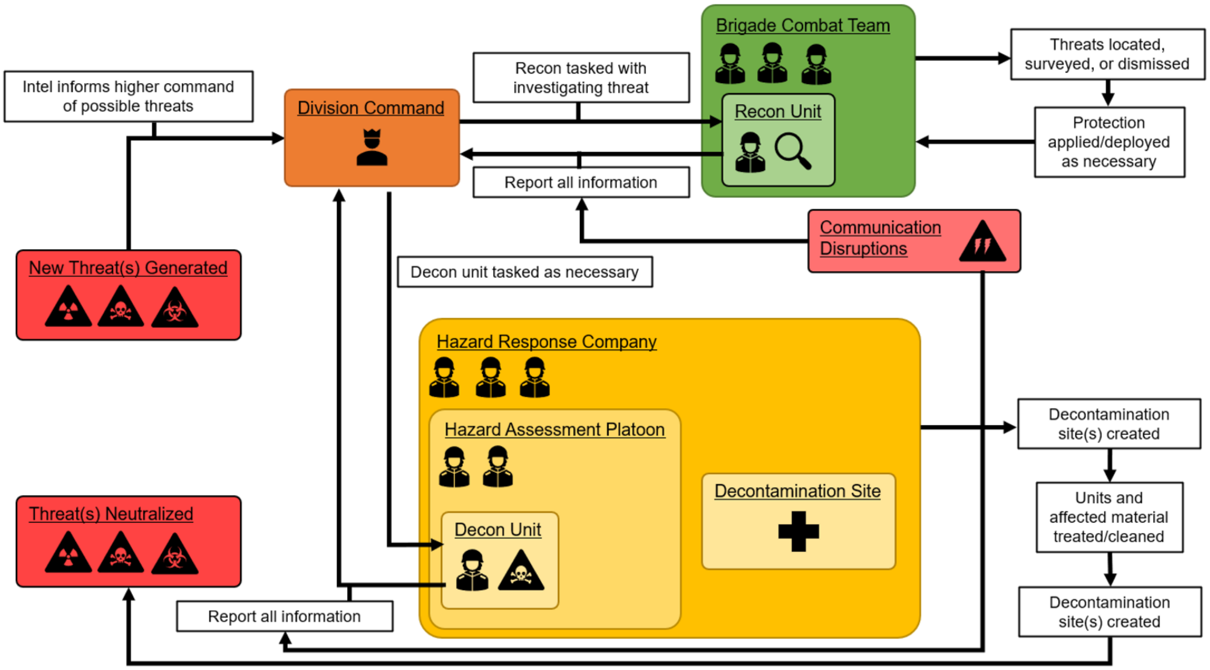



**Figure 1 Draft paper model for JPEO-CBRND field operations showing the organizations, actions, and order of events for a sample mission thread.**

## 1.3 Phase 2: Additive Manufacturing and JPEO Enterprise-Level Portfolio

### 1.3.1 Introduction: The Two Goals

As a part of the JPEO Phase 2 research (i.e., Additive Manufacturing and JPEO Enterprise-Level Portfolio), we investigated the possibility of using additive manufacturing (AM) as a part of the JPEO portfolio. To understand the use of AM, we set the following two goals:

**Two Goals**

- Goal 1: What can we do?
  - We went through the JPEO procurement portfolio.
  - We identified some of the potential opportunities within the portfolio.
  - We conducted a literature review on each AM application.
- Goal 2: What should we do?
  - We identified quasi-quantitative attributes and evaluated AM and TM technologies based on these attributes.
  - We identified quasi-qualitative attributes and evaluated AM, TM, and AM/TM hybrid technologies based on these attributes.

### 1.3.2 Enterprise Portfolio Considerations

System-of-Systems (SoS) are comprised of multiple heterogeneous distributed systems that are independently acquired and maintain their operational and managerial independence (Maier). Although systems are independent, the system-of-systems capability depends on effective collaboration between the systems and leveraging the interfaces. Most enterprises with the acquisition as a sizeable part of their modus operandi, when considering acquisition decisions, it becomes important to recognize the stakeholders, resources, operations, policy, and economics of not only one system but the entire SoS. Considering the SoS capability as a multifaceted enterprise, we develop research towards an information-centric framework that helps inform early-stage decisions on an enterprise level, specifically when new emerging technology is likely to challenge/replace a traditional one.

Important context for our work comes from the ambitious goals put forth in JPEO's plan for Digital Engineering (DE) and its related components in various engineering functions, such as Digital Thread for ILD. Much of the focus right now is on the "how" SoS modeling and a DE framework can aid acquisition decisions in JPEO-CBRND if additive manufacturing is the new state-of-the-art feature to be included in the family of technologies.

To construct JPEO as an SoS for their acquisition operations, we utilize hierarchical SoS modeling approach that has previously successfully been implemented (DeLaurentis 2004) along with a ROPE table to describe the components and interactions. Figure 2 shows the hierarchical categorization of elements within JPEO into α, β, γ, and δ levels.

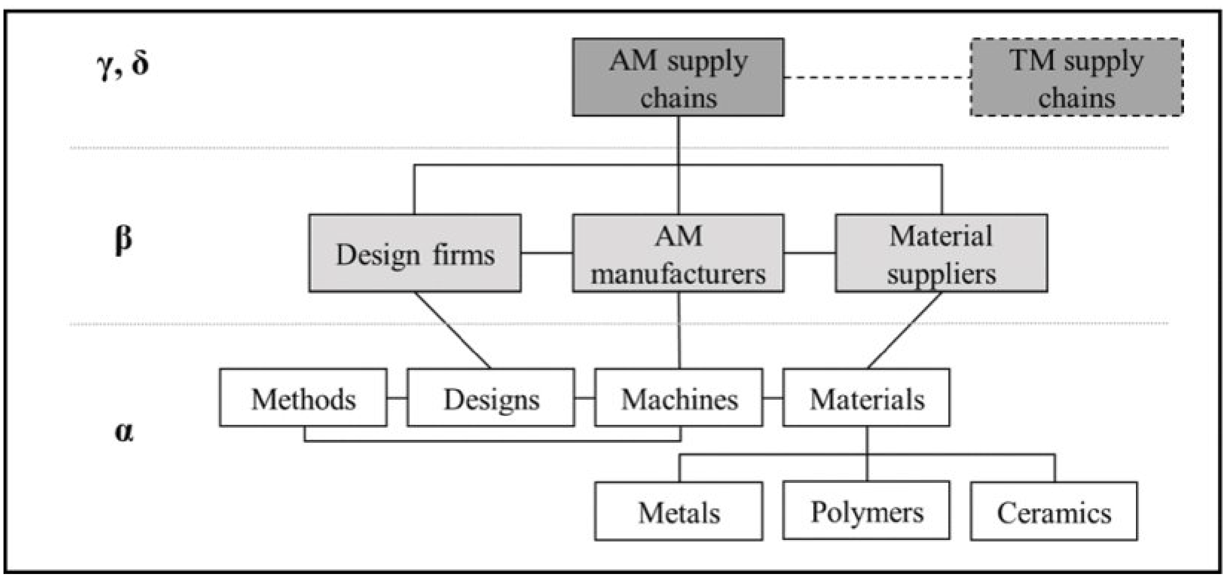



Figure 2 SoS levels of hierarchy in JPEO AM operations

ROPE tables are a tool to organize multiple levels of resource, operation, policy, and economic components of the JPEO-CBRND acquisitions system of systems relating to additive manufacturing.

**Table 1 ROPE table for JPEO CBRND AM acquisition**

| Levels | Resources | Operations | Policies | Economics |
|---|---|---|---|---|
| α | Machines, materials, designs, training materials, 3D software, maintenance equipment | Identification of viable α resources, operations of resources (e.g., machines) | Standards and qualifications of resources (e.g., machines, materials) | Cost comparison with producing, operating, maintaining AM vs. TM resources |
| β | Facilities and suppliers of resources (e.g., design companies) | Operations of facilities and suppliers, trade studies between different resources | Standards, qualifications, and training of suppliers and operators, consideration of performance parameters | Economics of buying/selling, operating, maintaining facilities and suppliers |
| γ | AM supply chains, 3D model repositories | Operations and logistics of AM supply chains: contract incentives for suppliers, acquisitions analysis | Standards and policies across supply chains (e.g., IP rights management) (including a request for AM impact in contracts) | Economics of AM supply chains: cost-benefit analysis of AM vs. TM equipment acquisition |

### 1.3.3 First Goal: What CAN we do?

In the following section, we identified the following four areas of opportunity in the JPEO portfolio that could be implemented using the AM technologies instead of (or in addition to) the TM technologies. Then, we conducted a literature review on each of the potential AM applications.

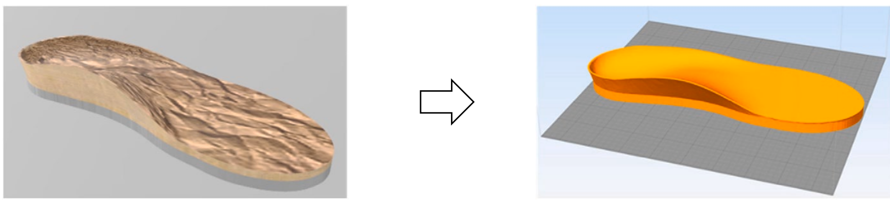
**Four Areas of Opportunities for AM**

- Ergonomic face shield components and respiratory/ocular protection capability
- Light-weight, low-cost biological surveillance system for aerosols
- Wearable electronics/sensors and carriers/holders for man-portable systems
- Repairs in the field and service for legacy systems

#### 1.3.3.1 Ergonomic face shield components and respiratory/ocular protection capability

We identified the ergonomic face shield components and respiratory/ocular protection capability as potential AM applications. These components may be produced using AM, rather than TM, for better ergonomics / customized fit since these components touch the end users' faces directly. To this end, engineers/developers can 3D scan the end user's face using a FARO arm (FARO), create a 3D CAD model, and print the ergonomic face shield components. The new advanced face shields and respiratory/ocular protection will protect the end-users against Chemical, Biological, Radiological, and Nuclear (CBRN) threats. Furthermore, the new technology can improve integration with individual combat equipment while minimizing or eliminating the unwanted/intrusive rubber on the face to unencumber the user while operating in a CBRN environment.

Our initial idea came from the literature review on creating the orthopedic shoe insole (Cui et al.), as shown in Figure 2. Compared to TM shoe insoles, AM shoe insoles (i.e., “orthopedic insoles”) can be made much more cost-effectively than TM shoe insoles since the 3D scanning process for AM can eliminate the trial-and-error approach for product fit, thereby creating a shorter lead time and a better/customized fit for end users.



TM shoe insole
(Produced from the trial-and-error process)

AM shoe insole
(Produced from the 3D scanned CAD/CAM data)

**Figure 3 TM vs. AM shoe insole comparison as the motivation for AM face mask**
(Cui et al.)

We can apply the same design principle to respiratory and ocular protection, where a customized fit on a face can produce more protection and better ergonomics for the end users. As we further conducted a literature review, we understood that there have already been attempts to produce face shield components and respiratory/ocular protections using AM technologies (Figure 3). As we saw the possibility of making the components of face shields using AM rather than TM, the end users in DoD can have a better-fit face shield for 1) improved ergonomics/comfort and 2) the prevention of contamination based on a better seal on/around the user’s face.


**Figure 4 AM face mask and air valve examples**
(Guvener et al.)

An additional reason why AM is suitable for this application is the AM process temperature is high. For instance, In fused deposition modeling (FDM), which is an extrusion-based AM technology (Figure 4), the material is melted for printing at high temperature (i.e., excess of 150°C) that eliminate (or reduce) biological agents that might be on the surface. Thus, while the FDM production is taking place, the component surfaces remain sterile. However, once humans start handling the part, there is a possibility for the virus to adhere to the component surface. Thus, the AM process is inherently sterile.

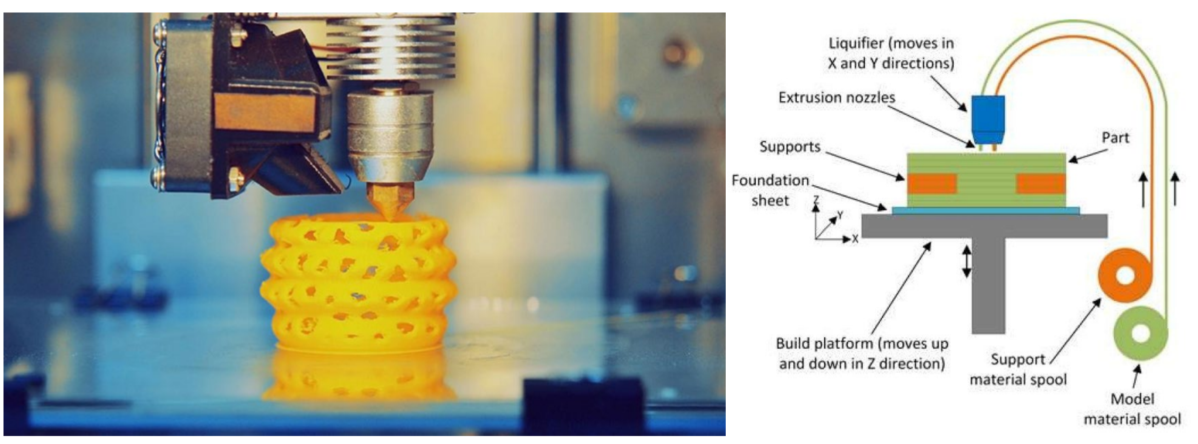



**Figure 5 FDM picture (left) and FDM schematics (right)**
(*The Complete Guide to Fused Deposition Modeling (FDM) in 3D Printing - 3Dnatives*); (Gebisa and Lemu); (Benesch and Redifer); (Abraham et al.)

As an example, to eliminate the COVID-19 virus (Abraham et al.), we heat the virus-containing objects for the following time:

- 3 minutes at a temperature above 75°C (160°F) or
- 5 minutes at a temperature above 65°C (149°F) or
- 20 minutes at a temperature above 60°C (140°F).

Thus, the AM process is inherently sterile due to the elevated temperature during the AM printing process. On the other hand, TM typically requires a complicated assembly process, compared to AM, since TM typically cannot match the part complexity of AM.

#### 1.3.3.2 Lightweight, low-cost biological surveillance system for aerosols

We identified the Biological Warfare Agent (BWA) aerosol detection device as a potential AM application. To this end, AM will allow the tactical, lightweight and low-cost biological surveillance system that detects, collects, and identifies BWA aerosols. We propose to use AM to create lightweight and low-cost outer frames for such systems.

There are works of literature that deal with chemical sensing for BWA aerosols. The detection, collection, and identification of BWA aerosols can be an excellent topic for AM technology implementation if we can create a device to achieve these goals using AM technology. To this end, fluorescence-based technology seems to be the most common technology. Thus, one possibility is to propose using AM technology to create the fluorescence-based detection system.

One example is the Ultraviolet Light Detection and Ranging (UV LIDAR) technology (Figure 5). The UV LIDAR system uses a laser to detect the presents of the BWA aerosols and gives early warning. The UV LIDAR technology is helpful since it can be used in the field, where soldiers can scan the area and detect the presence of BWA aerosols (Figure 6). If we can produce any of the UV LIDAR systems using AM technology, we may be able to create a low-cost detection device with a shorter lead time.

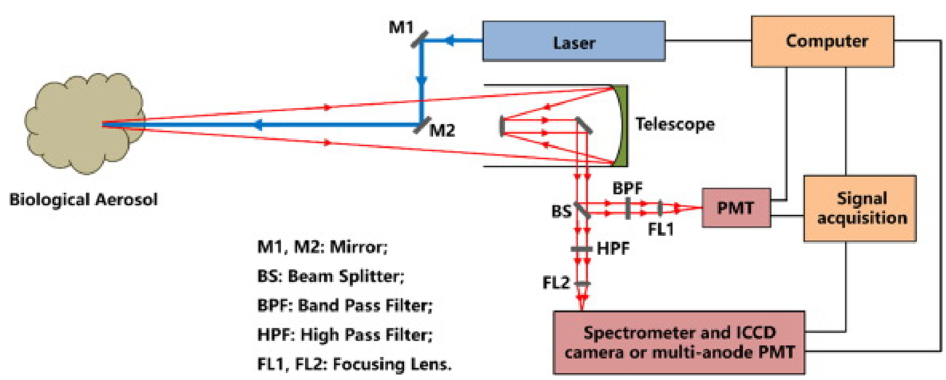



**Figure 6 Schematics of UV LIDAR system**
(Li et al.)

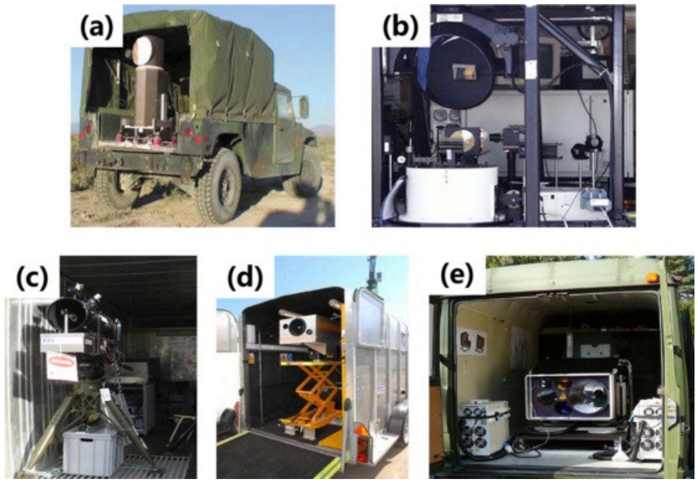



**Figure 7 Example of LIF LIDAR system or detecting biological aerosols**
(Li et al.)

Another possibility for the BWA application is to create an air-sampling collection unit (Figure 7) using AM technology, as some researchers published their air-sampling unit design. Then, using the established detection technology (e.g., UV LIDAR stated above) to detect the BWA.

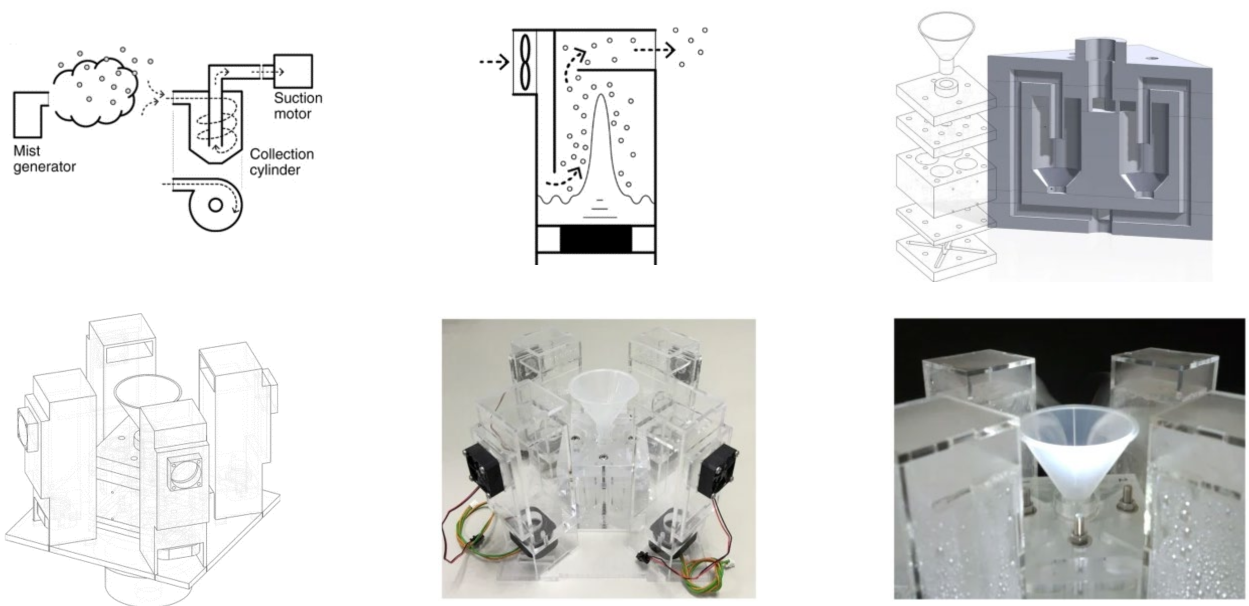



**Figure 8 Air sampling unit**
(Saito et al.)

### 1.3.3.3 Carriers/holders for man-portable systems and wearable electronics/sensors

We identified the wearable electronics/sensors and carriers/holders for man-portable systems (Figure 8). This application uses AM to create ergonomic carriers/holders and wearable electronics/sensors for man-portable systems.

A few years ago, the Naval Surface Warfare Center – Crane, Division (NSWC-CR) created a design challenge to improve the safety of man-portable lithium-ion batteries (*Lithium Battery Man Portable Hazard Containment Challenge*). According to the NSWC document, individual soldiers are envisioned to carry up to 12.5 lb. (5.7 kg) of battery equipment out of 50 lb. (22.7 kg) of total "man-portable" weight.

Based on the contents of the NSWC-CR document, the batteries account for 25% of the total transported individual weight. Since soldiers carry large lithium-ion batteries, the soldiers also carry additional electronics (e.g., sensors, radio, etc.). This means that it is critical for the design of the man-potable equipment to be as ergonomically friendly as possible. To this end, we can propose to create AM-produced carriers/holders and wearable electronics/sensors. We propose using 3D scanners to scan each user's body shape, as discussed earlier, using the FARO arm (FARO) to scan, create a digital model, and reverse engineer a product. To this end, ergonomically friendly carriers/holders and wearable electronics/sensors as a part of the "man-portable" equipment will significantly reduce the soldiers' stress.



Figure 9 Man-portable biological tactical detection system (JBTDS) (left) and sensor (right) (*JPEO-CBRND SMARTBOOK 1.0*)

### 1.3.3.4 AM for legacy components and repairs in the field

We identified the spare part production in the field/remote locations as a potential AM application. Similarly, we identified the spare part production for long-lead and legacy (i.e., discontinuous or obsolete) systems as a potential AM application. The common denominator for these applications is repair activity in the field.

As we conducted a literature review, we understood that Defense Logistics Agency (DLA) had its legacy parts already investigated for AM applications (Parks et al.). Also, there are recent pieces of literature that discuss the application of AM methodology in the legacy part (Blakey-Milner et al.), (Foshammer et al.), in which the researchers pointed out the following advantages of using AM for the legacy components: 1) production can take place any time (i.e., on-demand production), 2) there is no need to worry about often-unpredictable maintenance of legacy production system, and 3) a manufacturer can eliminate the legacy stock from the Wearhouse. Thus, as long as we maintain a digital engineering library and 3D printer with proper material, we can

### 1.3.4 SECOND GOAL: WHAT SHOULD WE DO?

**AM implementation for JPEO**

As we go through the AM implementation exercise for JPEO, we intend to show what applications can be better suited for using AM in the JPEO acquisition. When the application is deemed suitable for AM, the next step is understanding the trade-off of cost/ease of use/flexibility/performance. That is, AM should be able to provide a better performance, faster servicing, etc., than TM. Otherwise, we should keep using TM. At this point, we are moving toward a model-based decision approach since we will need to evaluate alternatives objectively. To this end, we need to identify/define the models. Also, as we try to understand procurement behavior, we will need to ask some questions related to the AM vs. TM decision.

**What models?**

- CAD/physical models -> performance, requirements
- Operational models / mission threads -> change in operations, flexibility
- Supply chain models -> cost, time
- AM models -> new requirements before a mission and when deployed

**Example of questions**

- What is the current or expected production volume of this product?
- What are some manufacturing details (i.e., cost, lead time, batch quantities)?
- How widely is the product being used?
- Is there one manufacturing point, and does the product have to be distributed worldwide?
- What AM capabilities does the military already have?

At this point, we have three potential approaches to incorporate the model-based approach to make decisions on AM acquisition as follows:

**Approach 1**: Create a decision support framework to compare the AM vs. TM (and potentially with AM/TM hybrid) to provide a framework for AM implementation decisions.

- What scenario if AM is more suitable than TM?
- What scenario if TM is more suitable than AM?
- What scenario if hybrid AM/TM is more suitable than AM or TM alone?

(Note: We chose to pursue Approach 1. This is the most straightforward approach.)

**Approach 2**: Create AM life-cycle decision support tool that can predict AM's overall cost/quality/safety impact. This includes (but is not limited to) design, manufacturing, supply chain, service/maintenance, warranty, and assistance after the product becomes obsolete.
(Note: We chose not to pursue Approach 2 due to the given timeframe being tight.)

**Approach 3:** Create an AM decision tool for the users to conduct a parametric study that could be used before making a decision on the following two points: 1) selecting AM components/materials and 2) purchasing AM equipment/technology
(Note: We chose not to pursue Approach 3 due to the given timeframe being tight.)

To summarize, we pursued **Approach 1** to create a decision support framework to compare AM vs. TM. In the following section, you will see these comparisons.

#### 1.3.4.1 How to include AM in Enterprise-level technology evaluation: AM vs. TM

**AM vs. TM:** We compared AM to TM using the following quasi-quantitative attributes.

- AM technology
  - 3D = 3D printing
- TM technologies
  - CNC = CNC machining
  - Poly = Polymer casting
  - Rot = Rotational molding
  - Vac = Vacuum forming
  - Inj = Injection molding
  - Ext = Extrusion
  - Blow = Blow molding
- Cost per part
  - $ = not expensive
  - $$ = slightly expensive
  - $$$ = expensive
  - $$$$ = very expensive
- Production volumes
  - $10^0 = 1$
  - $10^1 = 10$
  - $10^2 = 100$
  - $10^3 = 1{,}000$
  - $10^4 = 10{,}000$
  - $10^5 = 100{,}000$
- Lead time (minimum)
  - 12 h = 12 hours
  - 24 h = 24 hours
  - 36 h = 36 hours
  - 1 wk = 1 week
  - 2 wk = 2 weeks
  - 3 wk = 3 weeks
  - 4 wk = 4 weeks
  - 5 wk = 5 weeks
  - 6 wk = 6 weeks
  - 7 wk = 7 weeks
  - 8 wk = 8 weeks or more
- Part complexity (maximum)
  - 1 = Part design is not complicated
  - 2 = Part design is slightly complicated
  - 3 = Part design is moderately complicated
  - 4 = Part design is complicated
  - 5 = Part design is very complicated

Please note that in this study, we excluded the performance variables. We excluded the variables related to mechanical, thermal, and electrical properties/performance of materials since we intend to replace the existing parts using either AM or TM using the same materials currently used.

Figure 9 summarizes the AM vs. TM comparison by taking cost per part vs. production volume. The “3D” is the AM technology, whereas CNC, Poly, Rot, Vac, Inj, Ext, and Blow are the TM technologies.

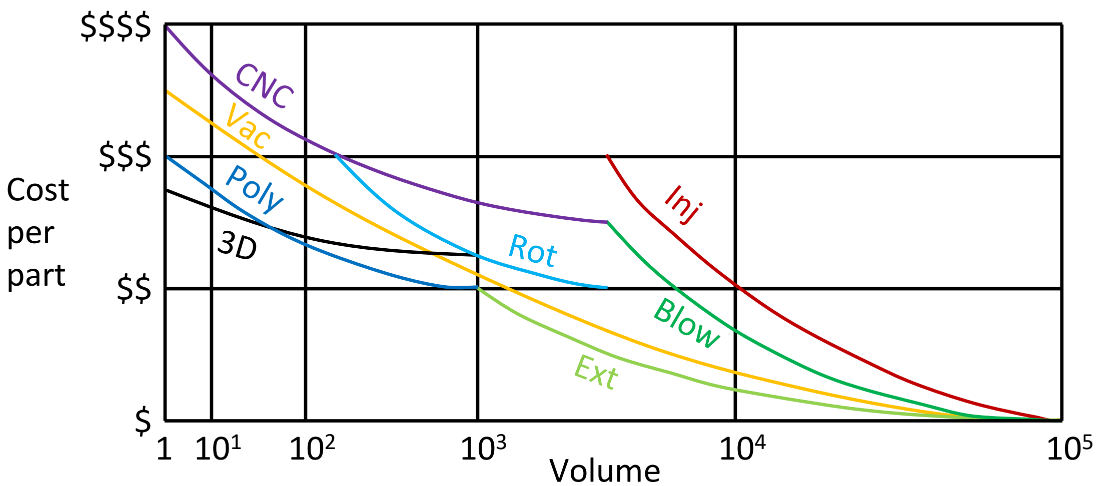



**Figure 10 Summary plot**
(Shi et al.)

Table 2 summarizes the AM vs. TM comparison by taking cost per part, total production volume, lead time, and part complexity. Using this table, the stakeholder can have a rough idea of the technology for their applications. Cost per part and production volume came directly from Figure 9. Table 3 exhibits the production volume based on AM and TM technologies. Table 4 demonstrates the production volume based on AM and TM technologies, which is the same as Table 3, but with cost per part information. Table 5 conveys the lead time based on AM and TM technologies. Table 6 outlines the part complexity based on AM and TM technologies. Table 3 - Table 6 follow the information depicted in Figure 9 and Table 2.

(Shi et al.)

**Table 2. Summary Table**

| Attributes | | AM | TM | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 3D | CNC | Poly | Rot | Vac | Inj | Ext | Blow |
| Cost per part | Min | \$\$ - \$\$\$ | \$\$ - \$\$\$ | \$\$ | \$\$ | \$ | \$ | \$ | \$ |
| | Max | \$\$ - \$\$\$ | \$\$\$\$ | \$\$\$ | \$\$\$ | \$\$\$ - \$\$\$\$ | \$\$\$ | \$\$ | \$\$ - \$\$\$ |
| Production volume | Min | 1 | 1 | 1 | $10^2$-$10^3$ | 1 | $10^3$-$10^4$ | $10^3$ | $10^3$-$10^4$ |
| | Max | $10^3$ | $10^3$-$10^4$ | $10^3$ | $10^3$-$10^4$ | $10^5$ or more | $10^5$ or more | $10^5$ or more | $10^5$ or more |
| Lead time | Min | 12-36h | 24h-2wk | 24h-1wk | 4-6 wk | 4-6 wk | 8-10wk | 2-4 wk | 4-6 wk |
| Part complexity | Max | 5 | 4 | 4 | 2 | 1 | 3 | 1 | 1 |

**Table 3. Production volume and technologies (basic)**

| Production volume | AM | TM | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3D | CNC | Poly | Rot | Vac | Inj | Ext | Blow |
| 1 | x | x | x | | x | | | |
| $10^1$ | x | x | x | | x | | | |
| $10^2$ | x | x | x | (x) | x | | x | |
| $10^3$ | x | x | x | x | x | (x) | x | (x) |
| $10^4$ | | (x) | | (x) | x | x | x | x |
| $10^5$ | | | | | x | x | x | x |

x = production is possible.

(x) = production is likely possible, although not explicitly stated in the plot.

**Table 4. Production volume and technologies (advanced)**

| Production volume | AM | TM | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3D | CNC | Poly | Rot | Vac | Inj | Ext | Blow |
| 1 | \$\$ - \$\$\$ | \$\$\$\$ | \$\$\$ | | \$\$\$ - \$\$\$\$ | | | |
| $10^1$ | \$\$ - \$\$\$ | \$\$\$ - \$\$\$\$ | \$\$ - \$\$\$ | | \$\$\$ - \$\$\$\$ | | | |
| $10^2$ | \$\$ - \$\$\$ | \$\$\$ - \$\$\$\$ | \$\$ - \$\$\$ | (\$\$\$ - \$\$\$\$) | \$\$ - \$\$\$ | | \$\$ | |
| $10^3$ | \$\$ - \$\$\$ | \$\$ - \$\$\$ | \$\$ | \$\$ - \$\$\$ | \$\$ - \$\$\$ | (\$\$\$\$) | \$\$ - \$\$\$ | (\$\$\$\$) |
| $10^4$ | | (\$\$ - \$\$\$) | | (\$\$) | \$ - \$\$ | \$\$ | \$\$ - \$\$\$ | \$ - \$\$ |
| $10^5$ | | | | | \$ | \$ | \$ | \$ |

Table 5. Lead time and technologies

| Lead time | AM | TM | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3D | CNC | Poly | Rot | Vac | Inj | Ext | Blow |
| 12 h | x | | | | | | | |
| 24 h | x | x | x | | | | | |
| 36 h | x | x | x | | | | | |
| 1 wk | (x) | x | x | | | | | |
| 2 wk | (x) | x | (x) | | | | x | |
| 3 wk | (x) | (x) | (x) | | | | x | |
| 4 wk | (x) | (x) | (x) | x | x | | x | x |
| 5 wk | (x) | (x) | (x) | x | x | | (x) | x |
| 6 wk | (x) | (x) | (x) | x | x | | (x) | x |
| 7 wk | (x) | (x) | (x) | (x) | (x) | | (x) | (x) |
| 8 wk | (x) | (x) | (x) | (x) | (x) | x | (x) | (x) |

x = production is possible.
(x) = production is likely possible, although not explicitly stated in the plot.

Table 6. Part complexity and technologies

| Part complexity | AM | TM | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3D | CNC | Poly | Rot | Vac | Inj | Ext | Blow |
| 1 | (x) | (x) | (x) | (x) | x | (x) | x | x |
| 2 | (x) | (x) | (x) | x | | (x) | | |
| 3 | (x) | (x) | (x) | | | x | | |
| 4 | (x) | x | x | | | | | |
| 5 | x | | | | | | | |

x = production is possible.
(x) = production is likely possible, although not explicitly stated in the plot.

To sum up the section on AM vs. TM, we have the following conclusions:

- Cost per part
  - AM: $$ - $$$
  - TM: $ - $$$$
- Total production volume
  - AM: 1 - 1,000
  - TM: 1 - 100,000 (or more)
- Lead time (minimum)
  - AM: 12 hours - 36 hours
  - TM: 24 hours - 10 weeks
- Part complexity (maximum)
  - AM: 5
  - TM: 1 – 4

**AM vs. TM vs. AM/TM hybrid:** We compared AM vs. TM vs. AM/TM hybrid using the following quasi-qualitative attributes.

- Data protection/security
- Data repositories/access
- Agility of operation
- Agility against new threats
- Digital twin
- Economically effective production lot size

Table 7 evaluates AM, TM, and AM/TM hybrid using the aforementioned quasi-qualitative attributes.

**Table 7. Evaluation of AM, TM, and AM/TM hybrid**

| Attributes | AM | TM | AM/TM hybrid |
|---|---|---|---|
| Data protection/security | Required | Required | Required |
| Data repositories/access | Required | Optional (OEM only) | Required |
| Agility of operation | Agile | Not as agile as AM | Agile. TM is the bottleneck. |
| Agility against new threats | Agile | Not as agile as AM | Agile. TM is the bottleneck. |
| Digital twin | Required | Optional (OEM only) | Required |
| Economically effective production lot size | $1 – 10^3$ | $10^3$ + (Note: TM production can be done as low as 1, although it may not be economically effective. | 1+ (Depending on application) |

## 1.3.4.2 Further considerations on AM at the Enterprise level

The following section indicates further consideration of AM implementation at the enterprise level.

- **Managing product data:** Data management is the key to success in AM. The most common product data format for AM is the STL format, which could be produced from various CAD systems (e.g., Dassault SOLIDWORKS, Dassault CATIA, Siemens NX, etc.). The stakeholder will want to implement a secure data repository to prevent the data leak since some of the 3D printed products in JPEO’s portfolio may be sensitive to the defense system. In addition, the repository should be able to keep track of multiple levels of design revisions since most products are the assembly of multiple components. Each assembly has multiple components, with each component carrying its revision levels. In a perfect world, everything fits; there are no assembly issues. However, in the worst case (i.e., when CAD design with incorrect revision levels is used), product assembly may become impossible due to the difference in the surface geometry, like a mating surface and tolerance.

- **Using product lifecycle management (PLM) tool:** The stakeholder may wish to use a product lifecycle management (PLM) tool to keep correct revision of product data throughout the life cycle, starting from conceptualization, development, prototype, launch, manufacturing, service, and legacy support. A component assembly is almost always required in a product, whether AM or TM is used to create components. To this end, having a smaller number of components using AM, rather than TM, will help mitigate the issue.

- **Managing personal data**: As a part of the AM data management for JPEO, some data are personal. For instance, scanned facial data for the ergonomic face shield components and respiratory/ocular protection results in scanned face data. To this end, the stakeholder may wish to establish the guideline to balance the following two competing requirements: 1) Ease of data access: The data must be protected with stringent control. 2) Data protection for end users: The data must be available for AM.

- **Considering legal implications of intellectual property (IP):** As the information moves from physical form to digital form (i.e., 3D scanning) and from digital form to physical form (i.e., 3D printing), the question of IP is not only related to the protection of IP, as described above, but also the legality of who owns the data. For instance, when someone scans your body to design and create a light-weight wearable electronics or ergonomically friendly carrier for man-portable, what the design engineer uses during the process is to create a product using the human body as a specimen. This process requires the end-users to agree to release the 3D scanned data of their body. In addition, this process may require approval from the Institutional Review Boards (IRBs) as described by the U.S. Food & Drug Administration (*Institutional Review Boards (IRBs) and Protection of Human Subjects in Clinical Trials | FDA*). Another example is the simple protection of IP of industrial goods. If a product in the JPEO portfolio is scanned, printed, and distributed without proper authorization, we will have IP legal issues. Thus, the stakeholder may need to review the process with the IP legal office when considering the possibility of implementing AM parts to replace the TM parts.

- **Addressing AM in different product stages**: The implementation of AM depends on the product maturity stage. Abstractly, the product maturity stages can be classified into introduction (i.e., proof-of-concept/prototype), growth (i.e., pre-production), maturity (i.e., mass production), and decline (i.e., legacy service). Some examples of this concept are shown below.
  - **Introduction**: Proof-of-concept/prototype
    Example: AM could be used to create a product in question to see if the brainstormed concept from the design engineering session works.
  - **Growth**: Pre-production (Small-quantity production)
    Example: AM could be used to create pre-production tools and fixtures. Also, AM could be used to develop the pre-production parts if the pre-production quantity is small, for instance, 1,000 or less
  - **Maturity**: Mass production (Large-quantity production)

Example: AM could be used to create production tools and fixtures, assuming that the surface of the AM is hard enough and withstand the wear and tear that go with the more significant production requirement. Also, AM could be used to create the production parts if the production quantity is small, for instance, 1,000 or less

- **Decline**: Legacy service
  Example: AM could be used to create service parts that are either difficult to obtain or no longer available from the manufacturer.

- **Implementing AM for various branches of DoD:** The ease of AM implementation may depend on the branch of DoD (e.g., Army, Navy, Air Force, Marines, and Coast Guard) with which the AM stakeholder work. For instance, 1) a certain branch of DoD may have a very stringent policy for the product requirement, so the experimentally made AM product may not be acceptable for this branch of DoD; 2) a certain branch of DoD may have a group culture that does not view the new AM technology insertion favorably; and 3) a certain branch of DoD is willing to try the new AM technology. In addition, even within the same DoD branch, a certain group of people is willing to accept (or pay for) the AM technology. For instance, special force operation groups may be willing to spend time and money developing the new AM parts.

- **Working with the DoD leadership team:** When implementing AM (or other new advanced manufacturing technologies), we may receive resistance from the people. This may be due to human nature to resist change (people do not want to change), or this may be due to some logical reasoning. Regardless of the reason for the change, it will be crucial for the stakeholder to receive consensus from the leadership team when making changes. For instance, if JPEO decides to work with the Army, JPEO will need to receive strong support from the Assistant Secretary of the Army – Acquisition, Logistics, & Technology (ASA(ALT)) leadership team. In this way, the AM implementation can be done in a top-down fashion.

### 1.3.5 VISIT TO CHEMICAL BIOLOGICAL CENTER (CBC)

Cesare Guariniello and Waterloo Tsutsui visited the U.S. Army Combat Capabilities Development Command Chemical Biological Center (CBC) and JPEO in Aberdeen Proving Ground, MD, on August 17, 2022. During the visit to CBC, we discussed various aspects of advanced manufacturing. After that, the Purdue team visited JPEO to discuss the project's progress and confirm the final reporting requirements.

#### 1.3.5.1 Lessons learned

The following section describes lessons learned during the CBC visit.

- **AM use/application at CBC**: While visiting CBC, we conducted an overview of AM/Advanced Manufacturing with the CBC representatives. The activities included the AM technique (i.e., both polymers and metals), 3D laser scan technique (i.e., FARO arm laser scan), specific AM applications (e.g., drones and pre-production tool builds using AM, and AM post-process (e.g., machining and coating) requirements. We also learned that CBC has been using AM since the 1980s. CBC maintains a highly competent AM and Advanced Manufacturing facility. The only major AM technique we did not observe at CBC was the ceramic AM. If CBC implements the ceramic AM, CBC can produce high-temperature resistant AM products. To this end, the CBC representatives told us that the ceramic AM is on their radar for the future.

- **3D scanning/reverse engineering capability at CBC**: CBC has the technical ability to scan parts for reverse scanning: We observe the use of the FARO arm and how it can be used to scan 3D objects to create point clouds (i.e., x-y-z coordinates of a 3D object surface). Also, the CBC engineer explained that the scanned point clouds might be used to create CAD data, and/or the scanned point clouds may be used to print a 3D object without going through the CAD data. This technology allows CBC to reverse engineer products, which can be a great resource when CBC tries to create parts without CAD data.

- **Creation and flow of data**: As stated above, CBC has the technical capability to create digital data using the FARO arm (i.e., 3D scanner). CBC also has the technical capacity to generate CAD data either 1) from manual creation (i.e., manual operation of CAD software) or 2) from 3D scan (transfer the 3D scanned point clouds into the CAD software). Furthermore, CBC has the ability to 3D print. Thus, we confirm the possibility of the following data flow: 1) physical to digital (i.e., 3D scanning process) and 2) digital to physical (i.e., 3D printing process).

- **Ownership and maintenance of data**: CBC described that data ownership depends on the product maturity and sponsor. We described the product maturity in an earlier section, where we classified the maturity in the following order: 1. introduction (i.e., proof-of-concept/prototype), 2. growth (i.e., pre-production), 3. maturity (i.e., mass production), and 4. decline (i.e., legacy service). We also showed AM application examples in each stage in the earlier section. What it means by the dependency of ownership is that at the first stage (i.e., introduction), the CBC engineers are trying to develop something that may or may not work. Thus, at this stage, the data is owned and maintained by CBC. However, when the product reaches the second stage (i.e., growth) and third stage (i.e., mass production), the ownership and maintenance of data is transferred from in-house CBC to either CBC's supplier or sponsor. Based on the conversation with CBC, we understood that CBC's in-house engineering responsibility mainly stays within Stages 1 and 2. Thus, CBC's data ownership and maintenance also remain within these stages.

- **Production of tools and obsolescence of products:** Based on our conversation with CBC, the production of manufacturing tools has excellent potential for AM use at CBC. For instance, CBC explained the pre-production manufacturing tools (e.g., injection-molding tools) could be made with AM since the pre-production quantity is low and does not result in repeated high stress, thereby allowing the AM-produced tools to be able to withstand the pre-production. On the other hand, the mass-production tools are not a great candidate for AM use since the AM-produced tools may not withstand the rigor of high-insensitive repeated stress during high-volume mass production.

- **Materials:** Due to the specific applications of interest to JPEO, some AM technologies already used in industry are applied to materials that might not be suitable, for example, for chemical threats. Some material might react in a harmful way to CBRN attacks. CBC has not performed any targeted studies in this domain. Therefore, this is another area that will require further consideration.

### 1.3.6 Recommendations

In this section we provide recommendations based on our research. The problem of including AM in the whole enterprise-level portfolio at JPEO is a large and complex problem, and it requires to include considerations on many aspects. Therefore, we focused on initial recommendations to JPEO for inclusion of AM in the JPEO portfolio.

- It is important for the stakeholders to identify what comparisons are the most useful for the acquisition decision in their portfolio.
  - AM vs. TM
  - AM vs. TM vs. AM/TM hybrid
- If the stakeholder is to pursue the AM/TM hybrid, the stakeholder may wish to clarify/define the term "AM/TM hybrid." For instance, the following questions may help.
  - Is the stakeholder interested in AM and TM components used on the same part? In other words, is the stakeholder defining the product that is assembled with AM and TM as the "AM/TM hybrid"?
  - Is the stakeholder interested in analyzing manufacturing networks that use both AM and TM? In other words, is the stakeholder defining the manufacturing networks that use both AM and TM as the "AM/TM hybrid"?
- The stakeholder may wish to identify low-production components as potential AM candidates.
- It would be beneficial for the stakeholder to understand what AM technology insertion is the most effective in the current TM lineup.
  - Cost is one of the most significant factors in procurement decisions.
  - Does the stakeholder feel the same about the cost being the most significant factor? In other words, will the decision be strongly motivated by cost savings?
  - Will the stakeholder be more motivated by agility against new threats and/or capability to respond to threats/robustness of response (than the cost savings)?
  - If the stakeholder is interested in the operational agility regarding the procurement, how could we include the cost of missed opportunity?
  - Can we convert the missed opportunity (i.e., delayed mission) into a cost figure? (i.e., it is difficult to deal with time and cost simultaneously. Thus, to this end, it is easier for us to deal with the single unit of "cost" to drive the decision-making process.)
- The stakeholder may wish to investigate how AM can be used in their portfolio instead of TM (i.e., replacement of the TM portfolio by AM).
- The stakeholder may wish to investigate how AM can be used in their portfolio in addition to TM (i.e., the addition of AM to the TM portfolio).

- The stakeholder may wish to investigate the scenario in which the AM/TM hybrid can provide a faster, more effective, and longer-lasting response to new threats rather than AM or TM alone.
- The stakeholder may wish to know the necessity of post-processing and issues on the AM part surface quality (i.e., surface roughness)
  - TM and hybrid AM/TM may produce a product with smoother surfaces compared to AM alone.
  - Generally, AM results in rougher surface texture compared to TM since the parts are printed layer-by-layer.
  - Rough surfaces are not desirable when dealing with mating surfaces, requiring post-processing (i.e., machining, which is TM).
- The stakeholder may wish to confirm that the remote AM site has post-processing capabilities before implementing AM technologies.

Further study is required to directly match policies and guidance documents (for example, the ASA(ALT) Implementation Guide for Advanced Manufacturing) to specific tasks and assessment. For example, since the Implementation Guide suggests the use of Cost-Benefit Analysis (CBA) on the applicability of Advanced Manufacturing, CBC could provide JPEO with their expertise on CBA for specific AM technologies and applications.

Other important points that JPEO will need to keep into account are the intellectual property, security of data, and definition of the owner of the models. Once again, these decisions will need to be taken based on each specific application. Wherever models reside, trade-offs need to be made for ease of access vs. security of the data storage (especially when personal data are involved, for example 3D scan of a face). More study is required on how industry addresses these problems.

## CONCLUSIONS

This research effort extended previous work in support of implementation of Digital Engineering at JPEO-CBRND. In particular, this year the team focused on requirements in terms of models for Digital Engineering. The team performed the research activities in two phases: (1) Development of an Agent-Based Model of the JPEO mission thread and (2) Additive Manufacturing and JPEO Enterprise-Level Portfolio. In the first phase, we developed an Agent-Based Model to simulate the JPEO mission thread related to unmounted reconnaissance and decontamination of a chemically contaminated site. We utilized the Model-Based Systems Engineering approach to represent JPEO's mission thread. Upon the completion of the first phase of research, we became familiar with JPEO's procedures and operations, which paved the way for the second phase of research. In the second phase, we investigated the possibility of including Additive Manufacturing in acquisition and procurement at the enterprise level at JPEO, as per Army directives and ASA(ALT) Implementation Guide. Within the second phase of research, we tried to answer the following two questions: "What can we do?" and "What should we do?". For the former, based on literature review, we identified which capabilities and technologies in the enterprise-level JPEO portfolio are suitable to be implemented with Additive Manufacturing techniques. For the latter, we found out very soon that the answer is strongly problem-dependent, as the choice whether to acquire technologies and capabilities based on Additive Manufacturing depends on a large number of variables: not only cost and performance, but also possible scenarios for the use of the capability, number of components required, ease of deployment and use, and more. In addition, considerations at the enterprise level include need for models to be developed, intellectual property, and access to data. Therefore, we identified a decision approach in support of JPEO decision-making on additive manufacturing versus traditional (subtractive) manufacturing. Based on this framework, we provided initial recommendations and lessons learned to JPEO, to guide the sponsor on future efforts in additive manufacturing implementation. As confirmed by interaction with CBC, an innovation center which is already considering and applying Additive Manufacturing, this kind of analysis and study needs to be specialized for specific applications, in order to reach a final decision about the adoption of Additive Manufacturing for each capability and technology in the whole JPEO portfolio. Further considerations include data property and security, materials, and reusability.

## TRANSITION PLAN

The following are potential areas where Purdue can assist JPEO with further activities:

- **Identification of current AM equipment capability for JPEO**: One possible transition approach is to review the potential AM equipment that JPEO can currently use without purchasing any additional equipment. That is, it is possible to create an extensive list of all AM equipment that JPEO can use now. Then, we can compare the AM equipment list with the JPEO's portfolio to see which products can be manufactured with AM without spending additional capital equipment funding on purchasing AM equipment. This activity may involve multiple branches of DoD. However, since we have already visited CBC, our first transition plan could start with the JPEO-CBC-Purdue collaboration. Then, if this collaboration is successful, we can branch out and seek more partners with AM capability.

- **Identification of future/potential AM equipment capability for JPEO**: After we understand what JPEO currently can use, we will be able to know what equipment JPEO wants to buy. This "want" (i.e., JPEO's motivation) should originate from what AM components JPEO wants to produce. For instance, if JPEO is looking for a 3D-printed high-temperature resistant part, JPEO will, most likely, need a ceramic part, which requires the AM equipment capable of printing ceramic parts. Based on the CBC visit and discussion on August 17. 2022, CBC is not currently equipped with ceramic AM. Thus, we will go through some type of capital equipment justification process to procure ceramic AM equipment for CBC. Then, after the equipment procurement, we will have CBC own and maintain the equipment for the ceramic AM production.

- **AM Portfolio Optimization**: After JPEO has enough AM machines (e.g., polymer, metal, and ceramic), we can conduct portfolio optimization. Since we are seeing a large number of AM equipment and AM products, we will need to come up with a systematic approach to optimize the combination of AM equipment and AM products. To this end, we can (1) identify critical variables for decision and establish a decision framework, (2) transform the identified framework and critical variables into an algorithmic view to make the most impactful AM decision, and (3) improve our System-of-Systems Robust Portfolio Optimization (SoS-RPO) tool to accommodate the JPO's needs on the AM portfolio optimization. Since AM is inherently connected with digital engineering and supply chain, we will also address these topics as a part of the AM portfolio optimization research.

The framework for analysis of Additive Manufacturing versus Traditional Manufacturing can be used by external sponsors, by adapting the framework to specific use cases.
JPEO identified potential partnership with CBC to apply Purdue framework on Cost Benefit Analysis for AM technologies.

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