

Additive Manufacturing in the DoD

Employing a Business Case Analysis

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Abstract

Additive Manufacturing (A/M), or 3D Printing, is the game changing family of technologies that enables the user to produce items of all types on demand from CAD files or data derived from 3D scanning. Materials as diverse as high performance polymers, carbon fiber and metal “super alloys”, as well as stainless steel, ceramics, sand and PLA plastics, are commonly used for A/M. Additively manufactured objects are currently in use by industry for a vast array of applications from flight critical commercial aviation parts to medical implant devices and more.

Long viewed as a passing fad, techies’ plaything, or “not ready for primetime”, A/M has matured into a technology that is revolutionizing industries and endeavors from aerospace and medicine to education and art. The potential benefits to military logistics include dramatic cost savings, weight reduction, and responsiveness to the warfighters’ needs.

In order to demonstrate and measure the benefits of A/M, in the Department of Defense (DoD), a rigorous Business Case Analysis (BCA) must be conducted. Since there are a number of possible use cases for A/M, each one must be examined individually to assess its viability for the DoD. Each use case must also be examined to determine the best A/M technology to choose for that application. This paper briefly defines the various A/M technologies and the use cases believed to be most appropriate for DoD logistics. It also identifies potential benefits and foreseeable challenges to implementation.

Finally, it outlines the methodology the Troika Solutions team proposes to follow in order to conduct such a study. Costs and benefits are often measured differently in the military than in industry. Readiness and availability at best cost are always key factors. Understanding of the government funding system is necessary to gain an accurate measure of benefit. Also, the unique attributes of A/M must be fully understood in order to accurately evaluate its costs, risks, and benefits.

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Introduction

Although Additive Manufacturing (A/M), or 3D Printing, was first demonstrated over 30 years ago, until recently its development largely took place in the shadows. High cost, limited capabilities, technical challenges, poor quality, and widespread misconceptions all contributed to the lack of attention. In the past few years, however, progress has accelerated dramatically. Most projections indicate that expansion of the technology will continue exponentially. New applications are being discovered or revealed every week.

Potential benefits of 3D printing now go far beyond speedy prototyping. Replacement of hard-to-get or obsolete items can be made possible in less time and at lower cost. Previously impossible complex geometries are now achievable. Dramatic weight saving is often the norm.

Industry observers sense, intuitively, that there are great benefits to embracing A/M. There is also a growing body of anecdotal evidence pointing to the overwhelming benefit to be gained. Conversely, there are many who focus on the potential pitfalls of using A/M technologies to replace conventional manufacturing techniques.

In fact, both of these positions are probably true. A/M is actually a family of technologies, each with its own strengths, weaknesses, and appropriate applications. In addition, the universe of materials available for use in A/M is huge, varied, and growing very rapidly. Broad generalizations regarding the Business Case for A/M are not useful. Instead, any meaningful Business Case Analysis (BCA) must be narrowly focused on a particular use case.

Purpose

The purpose of this paper is to advocate for the employment of a rigorous Business Case Analysis approach to determine the value of A/M in the DoD. This document will summarize the opportunities and challenges of A/M and lay out the Troika Solutions approach to developing a focused BCA that can support future decisions in regard to A/M. The intent is to provide a guide for meaningful and realistic study moving forward.

Additive Manufacturing Definition

ASTM Standard F2792-12A defines A/M as “A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication.” (1)

Additive Manufacturing Technologies

There are many different A/M machines and methods. In an attempt to order them and clarify the additive manufacturing universe, ASTM International, Committee F42 published the *Standard Terminology for Additive Manufacturing Technologies* which is derived from ISO 10303-1. The chart in Table 1 lists the broad process categories used in additive manufacturing.

Summary of the 7 Recognized Technologies

Technology	Description
Binder Jetting	Liquid bonding agent selectively deposited to join powder
Material Jetting	Droplets of build material selectively deposited
Powder Bed Fusion	Thermal energy selectively fuse regions of powder bed
Directed Energy Deposition	Focused thermal energy melts materials as deposited
Sheet Lamination	Sheet of material bonded together
Vat Photopolymerization	Liquid photopolymer selectively cured by light activation
Material Extrusion	Material selectively dispensed through a nozzle or orifice

Table 1 A/M Process Categories (1)

In an even simpler process classification Hod Lipson at Cornell University divides the printer world into two families (2):

1. Printers that squirt, squeeze, or spray
2. Printers that fuse, bind, or glue.

Within each of these broad technologies, there are numerous sub-classes with more being developed every week. Each technology is suited to a different application and material.

Following is a very brief description of each of these technologies:

Binder Jetting

This process is similar to 2D ink jet printing. A very thin powder bed layer of the selected material is deposited. Then a binding agent is selectively deposited in only those areas required for that layer in the manner that a document printer deposits ink. A new layer of

material is spread and the binding agent deposited. The process is repeated as often as needed. When complete, the block of powder is removed from the printer, and the loose “unbound” powder is separated from the printed object either by hand or with a blower. Some binder jet systems are able to print in full color.

Binder jet systems often provide fairly large build envelopes. The process is considered fast by A/M standards and less expensive than others.

Depending upon the material, post processing is often required to remove impurities and achieve the desired net-shape. When using this method for metal, the finished product must be sintered and infiltrated with a second material, which counters some of the speed offered by the process.

At least one manufacturer (Hewlett-Packard) has announced a binder jet process they claim will speed the process from 25 to 100 percent.

Material Jetting

This is sometimes referred to as “blown powder”. In this process, droplets of material are deposited directly onto a substrate. This process is often used for in situ repair of metal items. Cold spray or “kinetic spray” is usually considered a variation on material jetting.

Material jetting is capable of printing multiple materials at the same time. These combinations or alloys are sometimes referred to as “digital materials”.

Another application of this process prints in photopolymers or wax to use as investment casting patterns for jewelry or other small objects. When photopolymer materials are used, post processing includes curing.

Powder Bed Fusion

This process uses either a laser or an electron beam to selectively melt the desired portion of material in a powder bed. Depending upon the machine manufacturer, the process may be called selective laser melting (SLM); selective laser sintering (SLS); laser sintering (LA); direct metal laser sintering (DMLS), or electron beam melting (EBM). Both metals and polymers can be printed in this method although not in the same machine.

The majority of metal printing machines use this process. Challenges with this process include warping caused by residual stress due to the high temperature required. Powder bed machines tend to be more expensive than others, and EBM machines are near the top end of that cost curve, although they are faster and exhibit less distortion.

Directed Energy Deposition

Currently, this is a metal only process. Directed Energy Deposition comes in several “flavors”. In general terms, the material, either powder or wire, is deposited in line with

the energy source, either laser or electron beam. These machines are very complex and expensive. Parts produced require extensive post processing to attain the desired finish. However, the printing process is faster than most, and some of the largest and most impressive items have been printed using this process. Lockheed has printed spacecraft fuel tanks using this system.

Sheet Lamination

There are only two companies offering this process. One uses what is called Ultrasonic Consolidation to fuse layers of metal foils. The other sheet lamination process uses paper and adhesive to join the layers. The finished print is similar to wood. This process is normally used in conjunction with a cutting machine, making it a hybrid.

Vat Photopolymerization

This is the process originally discovered by Chuck Hull. Liquid photopolymer material is exposed to focused light, layer by layer. Applications for this process are limited but growing. Finished prints are often used to make molds for injection molding processes. Although this is the oldest 3D printing process, a recently announced version called Continuous Light Interface Production, or CLIP, is dramatically faster than any other additive manufacturing process. The finish is as good as, or better than, injection molding.

Material Extrusion

This is the simplest and least expensive A/M technology. It is the process used in most home 3D printing machines such as Makerbot or Cube. Materials are nearly always Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS) plastics. The material, usually in a filament, is heated and squeezed through a small orifice to selectively deposit in layers to form the desired object. This process requires support structures to be printed along with the item to prevent overhangs from sagging.

Although material extrusion is often used for basic “hobby” level machines, there are some very exciting applications including the Made in Space printer aboard the International Space Station (ISS). Oakridge National Labs (ORNL) used a Cincinnati material extrusion machine called the Big Area Additive Manufacturing (BAAM) machine to print a car body. And some are experimenting with using concrete in extremely large material extrusion machines to print structures.



Figure 1 Printed Shelby Cobra by ORNL

Machines and Materials

The recognized industry authority, Senvol, tracks both machines and materials in the Senvol Database (www.senvol.com/database/). That database now lists over 450 A/M machines and over 550 materials now being used for A/M. Figure 2 below illustrates the wide variety of both and breaks down the relative percentage of the major categories. (3)

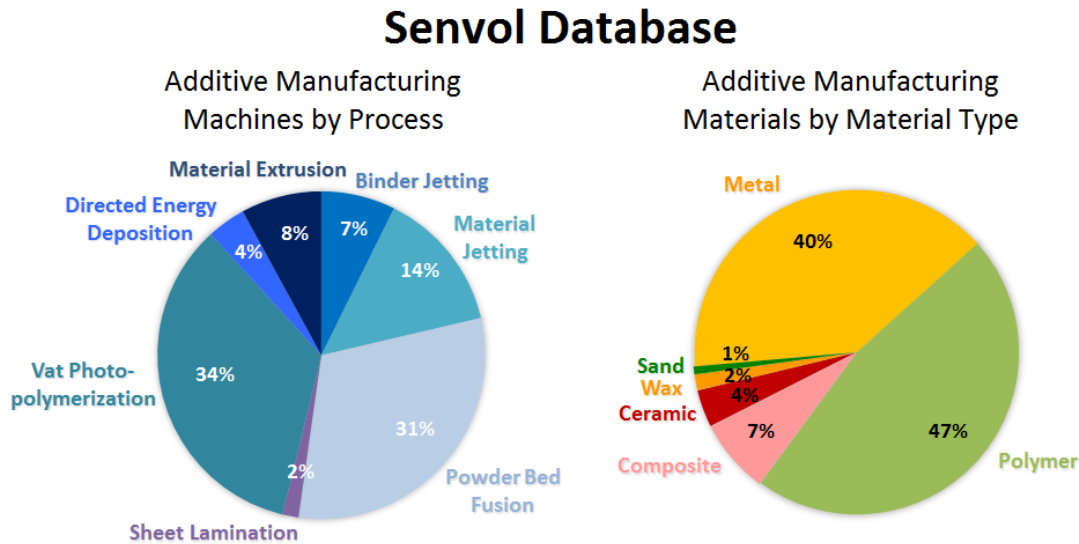


Figure 2 Senvol Database summary, used by permission

As can be seen from the pie chart above, polymers and metals make up the bulk of the materials used in 3D printing. However additional materials are being used in increasing quantity. Sand casting molds are printed quickly and efficiently saving time and money. Wax is printed to make molds to cast custom jewelry, works of art, and any items that require precision and a fine finish. Composites include nylon, carbon fiber, grapheme, and a host of others including a number of metal alloys not possible by any other method.

Common Applications for A/M

“A/M is used to build physical models, prototypes, patterns, tooling components, and production parts in plastic, metal, ceramic, glass and composite materials.” (4)

Prototypes

The first use of 3D printing and still the most common is rapid prototyping. The ability to create, test for form fit and function, and adjust quickly, saves money, speeds development and reduces waste that comes from design mistakes.

Custom Tools, Jigs and Fixtures



Figure 3 Image courtesy of Weltronics 3D Rapid Prototyping (24)

This is another common use of 3D Printing. These manufacturing aids are essential to efficient production of end use parts, assemblies, and products. It has been reported that 3D Printed tools, jigs and fixtures are commonly used in otherwise Traditionally Manufactured (T/M) operations. According to Lockheed spokesman Mark Johnson, "...we use hundreds of 3D-printed tools for F-35 manufacturing such as bracket locators and drill templates." (5)

Advanced Composite Structures (ACS) repairs composite components for the aerospace industry. They typically manufacture their jigs and fixtures in the traditional manner on Computer Numerical Control (CNC) machines. This is costly and time consuming. If the first copy of the needed item is faulty, the lengthy process must be repeated at additional cost and delay. In contrast, the needed fixture can be printed overnight at much lower cost. (6)

Method	Cost	Lead Time
CNC Machining	\$2,000	45 Days
3D Printing	\$412	2 Days
Saving	\$1,588 (79%)	43 Days (96%)

The chart in Table (2) reflects the savings possible by printing rather than milling needed jigs and fixtures

Table 2 Sample Cost Comparison

Models

A detailed model can assist in validating a complex design before incurring the cost of building a working prototype. Architectural models can facilitate refinement of building designs.

Dental/medical

Invisalign braces; custom dental work; personal hearing aids; prosthetics; bio-implants; joint replacements, and more make the medical/dental fields the most dramatic examples of the extraordinary potential benefits of 3D Printing. For example, the Stryker Corporation produces one million titanium hip replacements per year using A/M.

Obsolescence and Reverse Engineering

3D Printing and 3D scanning offer a powerful tool to address the issue of obsolescence and unavailability of needed items in all of life. If detailed technical data describing that item is available it can often be possible to simply manufacture a new replacement without the need for reverse engineering. However, if that data is not available, it is still possible to scan an item and reproduce the external geometry of that item as a first step in a reengineering process.

End use parts



Figure 4 GE 90
Sensor Housing

As 3D printing technology rapidly advances, more and more end use parts are being printed. Commercial airliners now have hundreds of printed parts on each plane. Up until recently that did not include so called “flight critical” parts. It was mainly ductwork, hinges, and brackets. However, General Electric recently received FAA approval to retrofit the cobalt-chrome sensor housing pictured in figure (4) on their GE90 engine which powers the popular Boeing 777. The picture in figure (5) on the right is the fuel injector from the new LEAP engine. It is currently undergoing flight testing. There will be 19 of them on each engine. Although weight

saving is a consideration for using A/M for these components, the greater impetus in each case is improved functionality over that which would be possible in T/M components. (7)



Figure 5 Leap
Engine Fuel Injector

Benefits

- **Low Cost for Short Manufacturing Run** – Because there is no need for tooling and set up, the per-part cost for one item is no more than for 100 or 1,000.
- **Speed** – As with the above, the ability to go directly from data to product and then to inspect, test, and correct in an iterative manner, speeds the finished item to the customer.
- **Mass Customization** – Using A/M, it is possible to customize each individual item. This is the capability that enables Invisalign braces, form fitting hearing aid carriers, or medical implants of all types.
- **Design for A/M** – Some of the most dramatic benefits made possible by A/M become available when items are designed for it.
 - **Light Weight** – This is particularly important to the aerospace industry. According to the National Aeronautics and Space Administration (NASA) it costs \$10,000 to put one pound into earth orbit. (8) Weight-saving is important in many other applications as well, such as improving fuel economy in automobiles.
 - **Otherwise Impossible Geometries** – The GE jet engine fuel injector shown in figure 5 is not only 25 percent lighter than a T/M manufactured fuel injector. It is also five times as durable. This is due to the unique design possible only through A/M. (9)

Challenges

- **Technical Data** – In order to gain the greatest benefit from A/M it will be important to possess complete technical data including 3D CAD or 3D print files. This is called the Digital Thread or a Model Based Definition. With this

data, it will be possible to replace physical inventory with virtual inventory. There are commercial enterprises doing this now for relatively simple products. Industry protection of proprietary intellectual property will be the greatest hurdle to finally achieving a Model Based Enterprise.

- **Qualification & Certification** – It is important to recognize that many 3D printed items are superior to their T/M counterparts. They are very often lighter, stronger, and more durable. In order to gain this advantage, parts must be designed for 3D printing and, more important, there must be a method of certifying that quality is in keeping with requirements.

If each printed item must be individually certified, much of the advantage of speed and reduced cost would be negated. The answer to this, according to a number of A/M practitioners, is to certify the material and the process. Some 3D printer manufacturers are incorporating a process monitoring system that is able to identify faults in the print process. However, to date none have offered the “closed loop” ability to detect faults, and correct them in real time during the build process. This will almost certainly be accomplished in the near future.

- **Standards** – The industry is maturing to the point that it has recognized the need for standardization in file formats, terminology, data structure, etc. The root of this issue is the nature of the growth the industry experienced over the past 30 years. Each new organization followed its own path and developed its own practices, standards, language, software, and methods. The reasons and the challenges are very similar to those encountered in the effort to achieve data interoperability among joint and coalition forces.

There are currently at least seven U.S. and European Standards Development Organizations (SDO) creating standards for this industry. America Makes recently sponsored a meeting of these disparate organizations to begin harmonization of their efforts in order to reduce conflicts, redundancies, and gaps. It will take years to sort out the individual practices that have developed over the past 30 years of technology development.

- **Intellectual Property (IP)** - There is no doubt that IP issues will be an obstacle to early adoption of A/M, particularly as it affects the Model Based Enterprise. According to John Hornick, an attorney specializing in this field, there will be a period of time when industry will defend their IP vigorously. He believes that in a few industries such as aerospace, IP will probably remain important. However, Hornick also states that:

“As democratization of design and manufacturing increases away from control, IP will become increasingly irrelevant.” (10)

Many in the industry believe that the issues will be overcome with creative solutions in a manner similar to the approach of the music industry. IP owners will sell data as well as, or instead of, physical items.

- **Skill** - The population of those proficient in this technology is small. Within the military, it is smaller still. This will need to be addressed as the technology is implemented. That, however, is not unusual. The military is constantly embracing and learning new technologies. That will be the easiest obstacle to overcome.
- **Security** - According to Albert Davis, Director, Science and Technology (S&T) Division, Office of Intelligence and Counterintelligence, Department of Energy (DOE), speaking at the ORNL A/M Summit, there are several national security issues associated with 3D printing to consider. Central to these concerns is the fact that the majority of 3D printing companies are not headquartered in the United States. This raises a host of potential threats and issues. In addition to possible espionage and sabotage, International Traffic in Arms Regulations (ITAR) issues must be considered.
- **Resistance to Change** - A hallmark of technological progress within most government agencies is caution. Often, perceived risk weighs more heavily than potential benefit. Also, as with most large organizations, there is an institutional inertia. The attitude being that, "We have always done it this way," and "If it ain't broke, don't fix it".

Potential Use Cases

Below are quotes from documents on Marine Corps Planning Guidance and the Expeditionary Environment. They are followed by two brief examples pertinent to such intentions. They reveal ways A/M technology can be applied to great benefit to the Marine Corps.

Expeditionary Environment – *The 36th Commandant's Planning Guidance states "The Marine Corps is a naval expeditionary force." (11)* That carries with it, great logistical challenges. A/M can be a key facilitator to lighten the logistical load and shorten the supply chain.

In the Marine Corps Installations and Logistics Roadmap (MCILR) The Deputy Commandant for Installations and Logistics (DC I&L) says of A/M: *"This capability provides manufacturing near or at the point of distributions, significantly shortening the logistics chain. Additive manufacturing has the potential to revolutionize how we*

think about our expeditionary logistics chain, especially if such capability can be sea based for forward-deployed forces.” (12)

- **Diminishing Manufacturing Sources and Material Shortages (DMSMS)** – This is a case in which manufacturers or suppliers either discontinue production or support of needed items. It is not the same as, but closely related to obsolescence. (13) This may occur as a result of a business decision due to lack of demand, changing technologies, or possibly because of a sole source supplier going out of business. A/M can be a tool to address the DMSMS issue by repairing existing parts as with the Directed Energy Deposition process also called blown powder or laser cladding. (4) Another approach is to use A/M to replace parts in a short production run as needed.
- **Virtual Inventory** – According to the U.S. GAO report dated February, 2015, the DoD currently maintains a total inventory worth \$98 billion. (14) That same report indicates that approximately \$7 Billion of that inventory is excess. Many studies of this subject indicate that the cost of maintaining inventory is approximately 25 percent of the value of the inventory per year. The Defense Logistics Agency (DLA) is in the process of compiling a list of items that would be appropriate for A/M. If data describing those items, also called the Digital Thread, were maintained in an appropriate database, the potential savings would run into the billions of dollars. In addition, it would be possible for needed data to be emailed to the required location in real time, speeding the supply chain and reducing shipping costs.

Business Case Analysis (BCA) Methodology

BCA is used to assess the return on investment of different courses of actions, analysis of alternatives, or economic analysis. The BCA methodology introduced here intends to examine the cost elements of using A/M in expeditionary and/or depot-level points of maintenance against T/M methods.

Analyze Product Lifecycle Costs

In order to develop accurate and credible cost projections the Troika Solutions cost estimating procedure follows a standard and repeatable process that addresses or resolves a problem statement proposed by the BCA owner. Simply stated, the process steps are: estimate initiation, research, assessment, analysis, and presentation. (15)

Determining the purpose of the cost estimate is an important step in any analysis since it lays the groundwork and direction of the cost estimating effort. The BCA leads with the purpose to resolve a clearly defined problem. The analyst must then determine the cost drivers and their interdependence to establish an effective order of study. Many assessment steps may be accomplished either sequentially or concurrently.

The cost estimating process is both repeatable and recursive. It follows a methodological process to ensure a compressive and thoughtful analysis. The use of integrated, consistent, and repeatable processes is intended to reduce and quantify risks and uncertainties. A repeatable process will enable consistent results; recursive will continually update and validate costs and assumptions, new data, discoveries, and projections. (16)

The Cost Estimating Process

The cost analysis process as defined by the GAO is a multistep process where the first step is to identify the purpose and develop an analysis approach. The figure below is from the GAO (15).

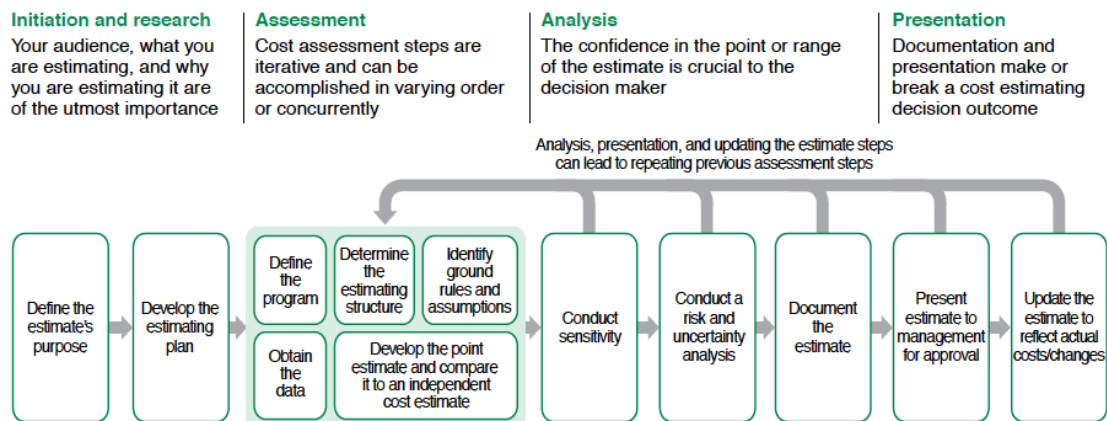


Figure 6 GAO Defined Cost Estimating Process (15)

The Process Steps:

1. **Define** - the estimate's purpose or problem statement, scope, and why the cost estimate is desired
2. **Develop** - the estimating plan of how the estimating team plans to accomplish the analysis
3. **Define** - the program characteristics; include identification of the operating environment, technology, schedule, and performance requirements
4. **Determine** - the estimating structure:
 - a. Work Breakdown Structure (WBS) or cost element structure
 - b. Four common analytical cost estimating methods and techniques used to develop cost estimates:
 - i. Analogy
 - ii. Statistical (Parametric)
 - iii. Engineering (Bottoms Up)
 - iv. Extrapolation of Actual Costs Methods

The cost estimating methodology used for a project or program progresses from analogy to extrapolation of actual costs methods depending upon project maturity and availability of data. The analogy method is appropriate to use early in the project life cycle when the system parameters are not yet well defined. As a system becomes more defined or mature, cost estimators are able to apply more robust methods such as statistical or parametric methods based on proven cost estimating relationship algorithms. (17) Due to the limited availability of A/M data, a parametric methodology is generally a good fit for estimating components. (18)

5. **Identify ground rules and assumptions** - for the boundaries of the analysis. This clearly identifies what is included and excluded; the project schedule; constraints, and technology assumptions
6. **Obtain the data** - this can be the most time consuming step in the process. Data collection must consider current relevant technical and programmatic data.
7. **Develop the point estimate** - compare it to an independent cost estimate to examine the differences. Validating costs, assumptions, and results will lead to a better supported estimate
8. **Conduct sensitivity of the cost elements to changing assumptions** - identify the effects on the overall estimate. This step will highlight the cost drivers
9. **Conduct a risk and uncertainty analysis** - determine the cost, schedule, and technical risk in each WBS element in the estimate. Identify the confidence in the point estimate and develop a risk management plan to track and mitigate risks
10. **Estimate documentation** - This includes all the steps from the purpose, program, schedule, technology, ground rules and assumptions, sources, methodology, risk, uncertainty, and sensitivity
11. **Present estimate** - to management for approval
12. **Update the estimate** - to reflect actual costs and changes which indicate adjustments in assumptions, technology changes, and programmatic changes to

keep the estimate as current as possible. Document all changes and describe the impact of the changes

Types of Cost Estimates and Purposes

Life Cycle Cost Estimates

Life Cycle Cost (LCC) can be defined as the total cost to the program owner of its program over its useful life. These costs include those for research and development, testing, production, facilities, operations, maintenance, personnel, environmental compliance, and disposal. The program's major stakeholders prefer to view life cycle costs grouped in a way that reflects its particular perspective. The three major ways of grouping and viewing program LCC are:

- **Appropriations** - for many government and military, the costs are categorized by funding appropriation. The program life-cycle costs are broken out along appropriation lines to develop internal budgets and submit budget requests.
- **Work Breakdown Structure (WBS)** - provides a framework for program and technical planning, cost estimating, resource allocations, performance measurements, and status reporting. The WBS should define the total system to be developed or produced. It needs to display the total system as a product-oriented family tree composed of hardware, software, services, data, and facilities. It must relate the elements of work to each other and to the end product. Program managers generally use the WBS as a support structure for planning and organizing the program activities.
- **Life-cycle cost categories** - The typical lifecycle cost categories are:
 - Research & Development (R&D)
 - Investment phase, including total cost of procuring the prime equipment; related support equipment; training; initial and reserve spares; pre-planned product improvements, and construction
 - Operating and Support (O&S) including cost of operating and supporting the project, all direct and indirect costs incurred in using the system (e.g., personnel, maintenance, and sustaining investment replenishment spares). The bulk of life-cycle costs occur in this category
 - Cost to dispose of the system after its useful life

Independent Cost Estimate

This independent estimate must be produced by an entity outside the development and acquisition chain(s) of command. Independent cost assessments are primarily used to support Acquisition Category (ACAT) programs at the required Milestone Decision Points.

Total Ownership Cost Estimate or a Cradle to Grave Estimate

Total Ownership Cost (TOC) is defined as the sum of financial resources needed to organize, equip, sustain, and operate the system while meeting national goals; policies and standards of readiness; environmental compliance; safety, and quality of life concerns. The

TOC for Defense systems consists of the costs to research, develop, acquire, own, operate, and dispose of weapon and support systems. The TOC of a defense system should be the same as its Life Cycle Cost (LCC).

Rough Order Magnitude (ROM) - is primarily used at project concept to determine the reasonableness and affordability of an endeavor. ROMs are primarily used for an initial cost estimate as a proof of concept.

Independent Government Cost Estimate (IGCE) - is primarily used by the government for acquisitions contract negotiations. IGCE's are principally contract negotiations focused as the period of performance would dictate.

Estimates at completion are primarily used for earned value management calculations to determine the contract execution performance and the ability of the project to execute the statement of work within budget and schedule.

BCA Types

Analysis of Alternatives (AOA)

AOA compares the operational effectiveness, suitability, and LCCE of alternatives that appear to satisfy established capability needs. Its major components are a Cost Effective Analysis (CEA) and cost analysis. AOAs try to identify the most promising of several conceptual alternatives. Analysis and conclusions are typically used to justify initiating an acquisition program. An AOA also looks at mission threat and dependencies on other programs.

Cost Effectiveness Analysis (CEA)

When an AOA cannot quantify benefits, a CEA is more appropriate. A CEA is conducted whenever it is unnecessary or impractical to consider the dollar value of benefits (e.g. when various alternatives have the same annual monetary benefits). Both the AOA and CEA should address each alternative's advantages, disadvantages, associated risks, and uncertainties and how they might influence the comparison.

Economic Analysis (EA) and Cost Benefit Analysis (CBA)

EA is a conceptual framework for systematically investigating problems of choice. Posing various alternatives for reaching an objective, EA analyzes the LCCE and benefits of each one, usually with a return on investment analysis. Present value is an important concept since this is when the time value of money is applied to the LCCE. This step is necessary to determine when expenditures for alternatives will be made over time. EA expands cost analysis by examining the effects of the time value of money on investment decisions. After cost estimates have been generated, they must be time-phased to allow for alternative expenditure patterns. Assuming equal benefits, the alternative with the least present value cost is the most desirable. It implies a more efficient allocation of resources.

Business Process Analysis (BPA)

The process owner examines individual organizational goals and objectives that in turn drive functional requirements. The BPA derives clear and understandable technical needs from these requirements in order to develop solutions to business problems. Possible solutions may include business process improvement, organizational change, strategic planning, and policy development.

Process improvement follows a methodology that includes a series of actions taken to identify, analyze, and improve existing business practices. The goal of process improvement is development of a systematic approach to help an organization optimize its underlying operation to achieve more efficient results.

Business Process Re-engineering (BPR) is defined as an integrated set of management policies, project management procedures, and modeling analysis design and testing techniques. This procedure analyzes existing business processes and systems; designs new processes and systems; tests simulations and prototypes of new designs prior to implementation, and manages the implementation process. BPR requires a restructure of the organization's business process that includes reestablishing, reorienting, or completely re-starting a new business division.

DoD has taken a holistic approach to BPR which includes a Portfolio and End-To-End (E2E) perspective. The Department defines BPR as a "logical methodology for assessing process weaknesses, identifying gaps, and implementing opportunities to streamline and improve the processes to create a solid foundation for success in changes to the full spectrum of operations". This definition covers various perspectives of BPR and aligns with the principles of Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities, and Policy (DOTMLPF-P) analysis. (19)

Ground Rules and Assumptions / Key Facts and Assumptions

Cost estimates that are early in the product life cycle are based upon limited information and require constraints upon estimate. These assumptions place bounds on the scope of the estimate and contain a series of statements that define the estimate parameters. Ground rules represent a common set of agreed upon estimating standards that provide guidance. (15) Assumptions represent a set of judgments about past, present, or future conditions considered as true in the absence of positive proof. The analyst must ensure that assumptions are not arbitrary; that they are founded on expert judgments rendered by experienced program and technical personnel. (18)

Typical ground rules include that key facts are known to be true like laws, regulations, and constraints. Assumptions are beliefs that something is true now or will be in the future, but for which there is no current proof. Assumptions are made based upon the best available knowledge to assign factors and probabilities that will drive the future decision. The reasonableness and validity of assumptions, as well as the need for new ones should be periodically reevaluated throughout the assessment.

Analyze and Quantify Costs and Cost Drivers

Typical costs from A/M and T/M are considered and compared. A/M expenses are broken out into in-house and service bureau charges. Service bureau charges are for the manufacture of the part or tool by an independent contractor using A/M technologies. The typical cost and cost drivers are compared to each other in Table 3, below:

	Traditional Manufacturing	In-House A/M	Service Bureau A/M
Engineering	More parts. Design less complex. More material waste when manufacturing	Design specifically for A/M. Virtual inventory of technical data. Designed for minimum material waste. Complex parts can be printed sometimes removing need for assembly. This can lead to weight reduction. Parts must be designed with printing orientation in mind. Printed parts are often anisotropic. Parts usually strongest in X&Y axes. Z axis depends on the layer property.	
	Part customization can be a slow and costly process. May require new casting molds and resetting of the learning curve	Part customization is easily achievable. Learning curve is not a critical factor in cost reduction	
Tools	Molds, casting, lathes, jigs, machining etc.	Necessary to purchase A/M machine, tools for surface finishing, sealant or coatings and tools to break off support structures from the printed part	Customer does not need any tool
Materials	Some alloys are better for 3D printing than for traditional manufacturing processes. (e.g. alloys that have been found to be difficult to machine)		
	Heavier parts	Lighter materials can be used in A/M. Plastics can replace metals in certain parts while still retaining the required properties. Part design can also reduce weight due to the production advantages of A/M	
	Tried and tested traditional materials	Limited materials available depending on A/M machine purchased	Many different materials available
Manufacturing	Depending on the technology and desired product finish, more or less post processing may be required for A/M than for T/M. Post processing must be assessed on a case by case basis.		Service bureau does post processing
	Larger knowledge/skill base for traditional manufacturing	Cost of purchasing A/M machines; number of machines needed; time and cost of training employees	Many A/M machines, technology, expertise available
Quality Control	Post-production testing	Voxel by Voxel in process monitoring is possible	
Safety	Maintain current safety requirements	Costly safety/ventilation precautions needed (OSHA regulations etc.); new facility potentially required	Customer not responsible for safety. Service Bureau must meet safety requirements
Facility	Factory or workshop	Garrison, forward areas, even in outer space	Available in many places CONUS or OCONUS
Inventory	Physical inventory of items	Store raw materials and digital thread until time to print part	

Table 3 Costs and Cost Drivers of Manufacturing Processes

Typical Manufacturing Cost Elements to Consider When Comparing A/M to T/M (Subtractive Processes)

The typical lead-time to acquire a part that is no longer in the supply chain is 12 to 18 months or more. The acquisition cycle begins with the market analysis, requests for information/proposal, statement of work, contract, and order quantities. Then add in the lead time to engineer, acquire materials, and tool and manufacture the part. All of this takes effort and time. (21)

Manufacturing cost estimating is defined as the set of techniques used to address issues unique to estimating in the manufacturing environment. (22) The manufacturing environment includes the effort and costs involved in the fabrication, assembly, and testing of a product or end item. It involves all the processes necessary to convert a raw material into finished items. With the amount of technical detail available in the manufacturing environment, generally engineering build-up or WBS approach techniques are used to estimate costs.

Manufacturing Costs include cost and effort and can be broken down as follows:

- **Engineering** - for scientific study, design, development of a task or WBS element
- **Manufacturing** - for fabrication, assembly, and testing of a part or end product
- **Quality Control** - to conduct testing, measuring, inspecting, and engineering compliance in each step to build the part or end product
- **Tooling** - to create molds, jigs, dies, fixtures, and patterns
- **Materials Costs** - raw materials, semi-fabricated materials, complete sub-assemblies, parts, and commercial off the shelf items
- **Tooling Materials and Test Equipment Costs** - effort and costs associated with the tooling and quality control efforts
- **Purchased Equipment** - that directly supports the manufacturing process
- **Overhead Costs** - allocated indirect costs and effort chargeable to a specified WBS element
- **General and Administrative Costs** - indirect costs associated with the management and general administration of the organization

A/M items are commonly created layer-by-layer. Knowledge of design intent is critical to ensure that greatest strength is attained in the desired direction. The process requires the manufacturing specialist to pay attention to the A/M part orientation during printing to maximize the desired strength properties.

A/M Cost Drivers

A/M can be a valuable tool for reverse engineering or replacement of a part that is no longer available. If digital technical data are not available (as is often the case), the object must be re-engineered. 3D scanning provides geometry of the object but does not provide functionality. It cannot scan internal structure of the object nor will it provide material

properties or design intent. This technical data is sometimes call the “Digital Thread” which, when available, can greatly reduce cost and time required to manufacture a replacement for an obsolete or unavailable item.

Direct Costs of A/M include the cost of equipment and varies upon the type of processing. Raw materials include metals, resins, and plastics. Facility modifications to support OSHA compliance may be necessary. Many metal raw materials are in powder form and, therefore, can be flammable or explosive.

A wide range of A/M materials are available. Many equipment manufacturers require the use of their own proprietary materials, usually adding to cost.

A/M requires highly skilled labor. Specialists are needed to recognize the proper file types, part geometry, orientation, and material requirements to maximize the form, fit, and function of the part.

Technology refresh for the printing hardware is assumed to be every two to five years due to the rapid technological growth of the industry. Technology replacement will probably occur before the hardware is worn out through normal use.

Indirect Costs would include the raw material inventory, machine set-up, and build failure/quality control.

Supply Chain Management requires the consideration and analysis of purchasing, operations, distribution, and integration coordination efforts.

Analyze and Quantify Benefits

A/M can often be the preferred method of manufacturing for small lots or “one-off” quantities. It is expensive and time consuming to produce items in small quantities by conventional means since it requires tool making, foundry work, milling, and finishing to make the desired part or tool. Complex geometries add to T/M costs when produced in low volumes. Production downtime costs are extremely high. A/M can increase the speed to market. When digital data that would be contained in the digital thread is available, this process is greatly facilitated.

T/M drives high inventory costs due to overstock items and long lead time for under stock or obsolete parts. On demand production runs require a T/M facility to gear up to production line. A/M can provide reduced inventory costs when there are many potential items that are required sporadically in small quantities. The facility is able to make the part as required and only needs to store the raw materials, thereby reducing the need for a parts inventory. A properly maintained Digital Thread as part of a Model Based Enterprise (MBE) can enable a “virtual inventory” of such items in a data warehouse.

Critical parts that are sole-sourced can create a supply chain risk if product availability is dependent upon supplier capability to deliver on a short production run item. When a part qualifies for A/M, the product is no longer dependent upon a legacy supplier.

Delivery of an end item to remote locations is difficult, time consuming, and expensive. Manufacturing certain parts on site using A/M in garrison or in an expeditionary environment cuts downtime and may reduce costs. With materials and power, A/M is possible by equipping a deployed printer. Location of a supplier versus the location of need may incur substantial import/export costs. On-site or near-site production will eliminate these costs.

A/M enables redesign to improve performance of an original design, thereby improving item functionality. Agile production is a strong capability multiplier for A/M(23). This shortens time-to-market duration and increases product diversity while quantity of diverse products decreases. The new products are less risky due to reduced tooling and product individualization. With A/M, there is no need to produce spare parts or to store legacy tooling. Rapid prototyping is a significant advantage of A/M since there is no lead time required. (24)

A/M generates less waste as compared to T/M. Machining can produce up to 90 percent excess of expensive materials such as titanium. A/M provides the capability of limitless designs if they are put into a digital file. Certain A/M machines and technologies provide the ability to use multiple materials in a single print. Customized products are enabled with small batch capacities and one-of-a-kind manufacturing.

Consider and Analyze Risks

A digital library, or virtual inventory, could contain the digital thread of obsolete parts or tools stored in memory to be used when needed. The ability to maintain the property rights of the digital thread, long term, is a consideration that will require analysis and mitigation. User access to the digital library will require controls to protect owner property rights.

Should there be no digital thread available for a required part, then the part will either require a complete reengineering, a digital scan of the object, or more likely both. Scanning the object will only capture the external geometry but will not capture internal components, material properties or the required functionality of the object.

Intellectual property rights of the digital thread will need to be protected to reduce the risk of infringement claims. Digital Rights Management (DRM) in some form will probably be the solution to this issue eventually.

There are sensitivities and uncertainties associated with either a garrison or expeditionary deployment that require analysis (e.g. material, quality requirements, availability of materials, printers, and power).

Due to the increased technological specialization associated with A/M the labor rates may be higher than the labor rates with T/M. However, with the reduced production cycle times associated with the short production runs and elimination of the need for tooling, the effort associated with A/M can be considerably less than T/M labor costs.

Materials for A/M can be specialized for the individual machine for which they were developed. This can lead to the material being proprietary to the machine manufacturer.

The range of printer and machine costs is significant due to the size of the part requirement; cycle time to produce the part; material requirements; complexity, and part specification.

Troika Solutions Capability

The key to the DoD gaining the greatest benefit from A/M will be a combination of diverse skill sets. Troika Solutions is uniquely positioned to identify and interpret the benefits, challenges, costs, and potential cost savings of A/M for various settings.

Obviously, an in depth understanding of the A/M technology along with a comprehensive network of resources, partners, and associates is essential. Troika Solutions' staff and partners are well credentialed in this area. They maintain memberships in the Additive Manufacturing Users Group (AMUG); the A/M Standards Setting Committee, ASTM F42; the National Center for Manufacturing Sciences (NCMS); the Additive Manufacturing for Maintenance Operations (AMMO) Working Group, and the Joint Technology Exchange Group (JTEG). Troika Solutions' Senior Additive Manufacturing Consultant is certified in A/M technology by the Society of Manufacturing Engineers (SME). Troika Solutions also maintains contact with a wide network of recognized experts in the industry including machine manufacturers; high level users; service bureaus; consultants, and attorneys.

In order to gain the greatest benefit from A/M it is vital to understand the make-up of the "Digital Thread". This is the technical data that describes the item. It includes 3D CAD drawings, material specifications and properties, certification and qualification parameters, and more. The digital thread should also include usage, history and failure data, and results of Reliability Centered Maintenance (RCM) analysis. Cost, source of supply, and inventory availability are also important. In short, the digital thread is the DNA of the item and all its available data.

Troika Solutions and its team members have an extensive history in the data management and analysis fields. They have conducted award winning efforts in Sense & Respond Logistics (S&RL); RCM Analysis; Total Lifecycle Management; Data as a Service; Data Interoperability (joint service as well as coalition); Master Data Management; Sourcing Broker, and much more. In addition, related efforts have included Automated Inventory Management; Asset Health Monitoring; The Internet of Things; Mesh Networking; Portable Fluid Analysis, and others.

Troika Solutions is well positioned to conduct AOA or BCA to illustrate the many potential benefits the DoD can gain from A/M capability deployment. Troika Solutions in-house cost team consists of a senior and junior cost analyst with a combined 16 years of DoD costing experience. Troika Solutions cost team has a history of building life cycle cost models; business case analyses; service pricing models, and Planning, Programming, Budgeting, and Execution System (PPBES) estimates.

The Troika Solutions cost team recently completed the Data as a Service BCA for the Command Control Communications and Computer (C4) Department of the Marine Corps Logistics Command. The Troika Solutions team also recently completed a cost estimate

to install Radio Frequency Identification (RFID) tags to Marine Corps Principal End Item (PEI) hardware units. Troika Solutions' senior cost analyst supported the Marine Corps Installation and Logistics (I&L) Information and Integration Office (I2O) program management and cost estimating activities.

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Acronym List

Acronym	Description
A/M	Additive Manufacturing
ABS	Acrylonitrile Butadiene Styrene
AMMO	Additive Manufacturing for Maintenance Operations
AOA	Analysis of Alternatives
BAAM	Big Area Additive Manufacturing
BCA	Business Case Analysis
BPR	Business Process Re-engineering
CAD	Computer Aided Design
CEA	Cost Effectiveness Analysis
CLIP	Continuous Light Interface Production
CNC	Computer Numeric Control
CONUS	Continental United States
DaaS	Data as a Service
DC I&L	Deputy Commandant Installations and Logistics
DLA	Defense Logistics Agency
DMLS	Direct Metal Laser Sintering
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DoD	Department of Defense
DOTMLPF-P	Doctrine, Organization, Training, Materiel, Leadership, Education, Facilities, and Policy
E2E	End to End
EA	Economic Analysis
EBM	Electron Beam Melting
FAA	Federal Aviation Agency
GAO	Government Accountability Office
IGCE	Independent Government Cost Estimate
IP	Intellectual Property
ISO	International Standards Organization
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
JTEG	Joint Technology Exchange Group
LCC	Life Cycle Cost

<i>Acronym</i>	<i>Description</i>
LCCE	Life Cycle Cost Estimate
MCILER	Marine Corps Installations and Logistics Roadmap
MDM	Master Data Management
NASA	National Aeronautics and Space Administration
NCMS	National Center for Manufacturing Sciences
O&S	Operations and Support
OCONUS	Outside Continental United States
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Health and Safety Agency
PLA	Poly Lactic Acid
PPBES	Planning, Programming, Budgeting, and Execution System
R&D	Research and Development
RCM	Reliability Centered Maintenance
ROM	Rough Order of Magnitude
S&RL	Sense and Respond Logistics
SDO	Standards Development Organization
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SME	Society of Manufacturing Engineers
T/M	Traditional Manufacturing
TLCM	Total Lifecycle Management
TLCSM	Total Lifecycle Systems Management
TOC	Total Ownership Cost
WBS	Work Breakdown Structure

Table 4 Acronym List