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:

<table>
<tr><th></th><th>Traditional Manufacturing</th><th>In-House A/M</th><th>Service Bureau A/M</th></tr>
<tr><td rowspan="2">Engineering</td><td>More parts. Design less complex. More material waste when manufacturing</td><td colspan="2">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.</td></tr>
<tr><td>Part customization can be a slow and costly process. May require new casting molds and resetting of the learning curve</td><td colspan="2">Part customization is easily achievable. Learning curve is not a critical factor in cost reduction</td></tr>
<tr><td>Tools</td><td>Molds, casting, lathes, jigs, machining etc.</td><td>Necessary to purchase A/M machine, tools for surface finishing, sealant or coatings and tools to break off support structures from the printed part</td><td>Customer does not need any tool</td></tr>
<tr><td rowspan="3">Materials</td><td colspan="3">Some alloys are better for 3D printing than for traditional manufacturing processes. (e.g. alloys that have been found to be difficult to machine)</td></tr>
<tr><td>Heavier parts</td><td colspan="2">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</td></tr>
<tr><td>Tried and tested traditional materials</td><td>Limited materials available depending on A/M machine purchased</td><td>Many different materials available</td></tr>
<tr><td rowspan="2">Manufacturing</td><td colspan="2">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.</td><td>Service bureau does post processing</td></tr>
<tr><td>Larger knowledge/skill base for traditional manufacturing</td><td>Cost of purchasing A/M machines; number of machines needed; time and cost of training employees</td><td>Many A/M machines, technology, expertise available</td></tr>
<tr><td>Quality Control</td><td>Post-production testing</td><td colspan="2">Voxel by Voxel in process monitoring is possible</td></tr>
<tr><td>Safety</td><td>Maintain current safety requirements</td><td>Costly safety/ventilation precautions needed (OSHA regulations etc.); new facility potentially required</td><td>Customer not responsible for safety. Service Bureau must meet safety requirements</td></tr>
<tr><td>Facility</td><td>Factory or workshop</td><td>Garrison, forward areas, even in outer space</td><td>Available in many places CONUS or OCONUS</td></tr>
<tr><td>Inventory</td><td>Physical inventory of items</td><td>Store raw materials and digital thread until time to print part</td><td></td></tr>
</table>

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 involve 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

Acronym	Description
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