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Shrinking the "Mountain of Metal": The Potential of Three Advanced Technologies

6 June 2017

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Abstract

Military operations create large amounts of damaged equipment, referred to as "mountains of metal." Traditional and current strategies for shrinking the mountain include shipping most equipment to U.S. depots for repair and overhaul. Three advanced technologies—three-dimensional laser scanning, additive manufacturing, and product lifecycle management—can potentially save costs by relocating and accelerating repair operations. Published forecasts of the evolution of these technologies formed the basis for scenarios of their application to shrinking the mountain at U.S. depots, in-theater support facilities, and at forward stations: current use, near-future use, and distant future use. Knowledge Value Added modeling was applied to four technology adoption scenarios (traditional and the three listed) to the Army's up armor HMMWV fleet to estimate returns on investment for each scenario, costs, and potential savings. Cost savings potential of $1.8 billion in the up armor HMMWV fleet and over $21 billion in operations similar in scale to those in Iraq and Afghanistan are estimated. Conclusions include a recommendation to accelerate the adoption and use of these advanced technologies for equipment repair to shrink the mountain of metal.

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Introduction

Military campaigns such as Operation Iraqi Freedom (OIF), Operations Enduring Freedom (OEF), and the war in Afghanistan require vast amounts of equipment and a substantial supply chain to support operations. For example, more than 750,000 end items (e.g., boats, aircraft, vehicles, weapons) valued over $36 billion were deployed in Afghanistan in 2007. The Army estimates that it has deployed 40% of its equipment to support OIF and OEF, and the Marine Corps estimated deploying 22% of its total fleet assets in Iraq (Solis, 2006). The Marine Corps estimates that 40% of its ground equipment, 50–55% of its communications equipment, and 20% of its aircraft equipment were supporting operations (Solis, 2006). Much of this equipment is utilized or damaged, requiring repair. This has created an “enormous” (the GAO’s term, Solis, 2006) amount of deployed equipment to be diagnosed and then repaired, overhauled, or disposed.

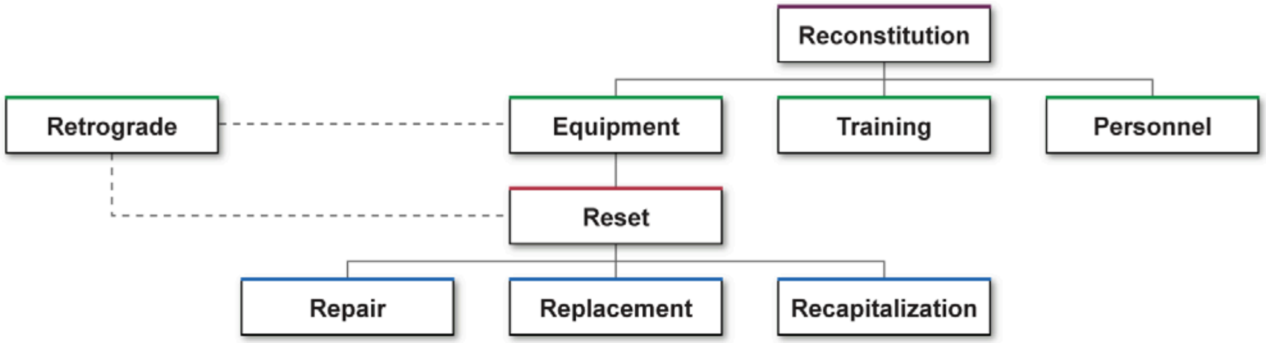
It is the disposal of this materiel that creates an opportunity for better, less-costly options. This collection of equipment has been referred to as “the Mountain of Metal,” referred to hereafter as “the Mountain.” Using advanced technologies, that is, additive manufacturing, product lifecycle management and three-dimensional laser scanning technology, a large portion of the waste incurred by this Mountain of Metal can be eliminated. This study reviews and quantifies the potential benefits of using these three technologies to reduce the costs of a large portion of this Mountain.

The Army and Marine Corps have similar systems for managing equipment in support of operations. (See Solis, 2006, for parallel descriptions of the two systems.) The Army’s system is significantly larger in volume and has been reviewed more extensively. The following research is based upon the Army system, with relevant notes concerning the Marine Corps. Conclusions are drawn concerning the cost reductions possible with the acquisition and use of the three advanced technologies to both services.

Although major combat operations ceased in Iraq and Afghanistan as of late 2014, the Mountain remains a major Department of Defense (DoD) challenge. The

DoD’s reconstitution process is the process whereby materiel from the Mountain can be certified for reuse, making it available again for operational use (Government Accountability Office [GAO], 2016). Figure 1 depicts the components of reconstitution. The Army’s reset (the Marine Corps uses the term “recovery”) processes are a part of reconstitution and can benefit from the adoption of the three advanced technologies investigated here via a larger percent of reuse of the material in the Mountain.

Figure 1: Relationship Between Reconstitution, Retrograde, and Reset Activities (GAO, 2016)



Source: GAO analysis of Department of Defense information. | GAO-16-414

In theater operations, increased use and harsh operating conditions create the unusable equipment that winds up in the Mountain. Equipment usage rates are several times higher than during peace time.[1] More specifically, the Army reported rates two to eight times higher and the Marine Corps reported rates four to nine times higher than peacetime rates (Solis, 2006). General Peter Schoomaker, the Army’s Chief of Staff, reported to the House Appropriations Subcommittee that “we’re wearing out helicopters and trucks, Humvees, tanks at rates that are six, eight, 10 times, in some cases, what we’re programmed for” (Hendren, 2007). These usage rates lead to dramatic increases in the costs, not to mention the lack of availability of the equipment, in theater operations.

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[1] See the Congressional Budget Office (CBO, 2007) study for usage rate details for several types of large equipment and an argument that envisioned Cold War operating tempos should be the benchmark for current operating rates, not peace time tempos.

Making more of the equipment in the Mountain available for reuse would dramatically reduce costs. The Army needs about $13 billion per year for each year of the conflict and for several years thereafter to address the costs of eliminating the Mountain (Hendren, 2007). The Marine Corps costs to eliminate the mountain approaches $1 billion (CBO, 2007).

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Processes for Shrinking the Mountain

The DoD Supply Chain Materiel Management Policy (2011) specifies five processes by which equipment should be disposed of including how the Mountain can be reduced. In order of decreasing priority, the processes for disposing of materiel from contingent operations are as follows:

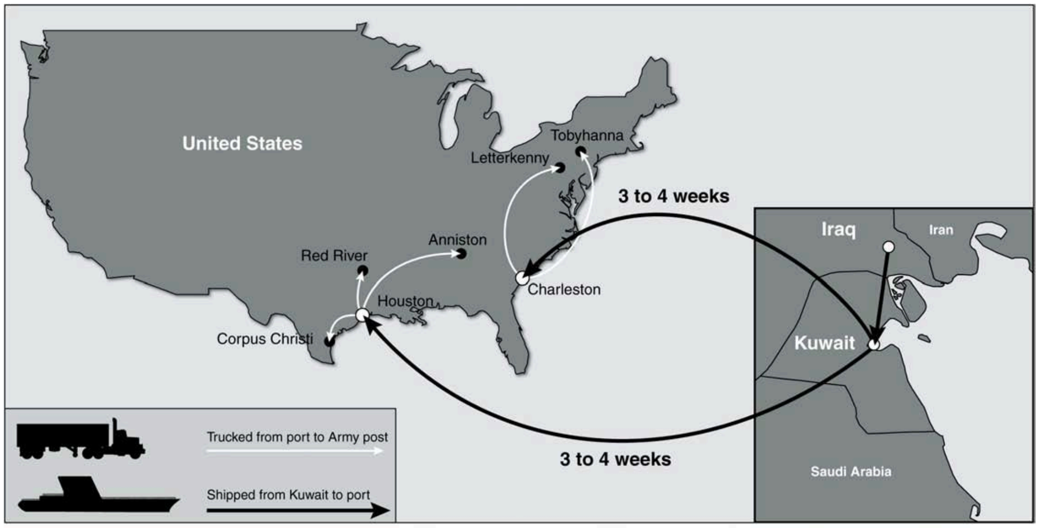
1. Consume in theater
2. Reutilize within DoD and other U.S. entities
3. Retrograde (return to U.S. depots) to reset (restore to full capability) U.S. forces
4. Transfer or donate to allies or partner nations
5. Turn-in to Defense Logistics Agency Disposition Services for disposal because damage makes reset inappropriate

The efficient repair and overhaul of equipment, using the three advanced technologies, can redirect much equipment for future usage that might otherwise be scrapped (the lowest priority process).

The Traditional Strategy

The traditional Army approach to managing equipment requiring significant maintenance, repair, or overhaul (MRO) is that equipment stays with the unit that it is deployed with and returns to the United States after deployment, where MRO are performed at one of five depots (Figure 2). Some equipment is repaired near forward stations by maintenance companies, reducing transportation costs and saving time, and maximizing availability. However, according to the CBO, “In general, until 2007, Army units rotated in and out of the theater roughly annually, and as a result, most equipment remained in the theater for about a year and was then returned to its unit’s home station to be reset [be returned to full capability]” (CBO, 2007). The unit deployed to replace the returning unit brings their own equipment. This process was used for hundreds of thousands of pieces of equipment deployed to Iraq, Afghanistan, and surrounding areas (CBO, 2007).

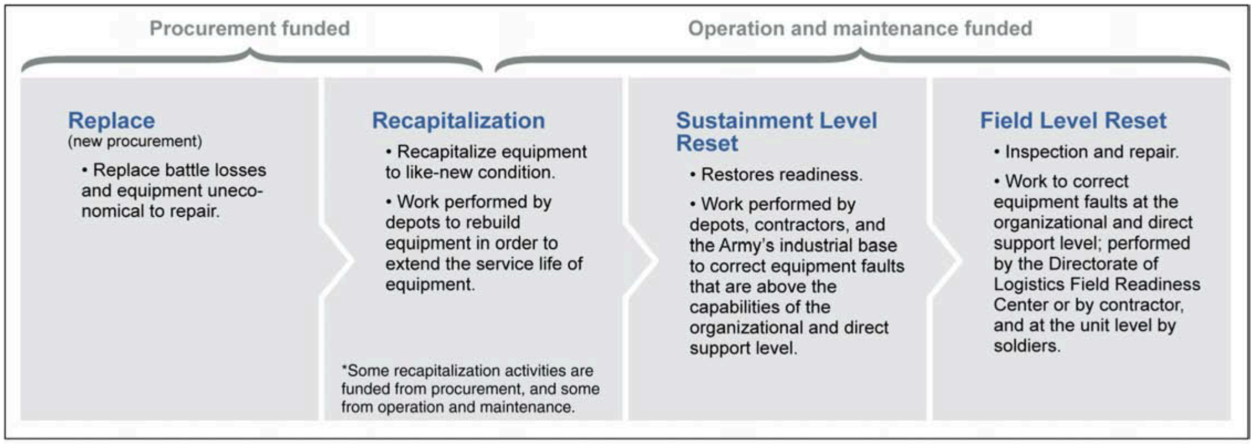
Figure 2: Retrograde of Equipment Leaving Southwest Asia and Returning to the United States for Reset (GAO, 2012)



Source: GAO analysis of DOD data.

The Army uses the reset process to manage damaged equipment. “Reset” is the term for “a series of repairs, recapitalization, and replacement actions to restore unit’s equipment to a desired level of combat capability” (CBO, 2007) (Figure 3). This process repairs all damage and performs all routine maintenance. Equipment is returned to conditions known as “10/20,” referring to the levels specified by the 10/20 technical manuals which call for all shortcomings and deficiencies to be repaired, and all routine maintenance performed (Taktikz, 2017). Equipment to be repaired, is often relocated away from forward locations to a reset location through a process referred to as “retrograde” (Acquipedia, 2017). The Marine Corps published a reset implementation plan and the Army published information on aspects of the reset process in 2016 (GAO, 2016). Figure 3 (GAO, 2012) illustrates part of the reset process.

Figure 3: The Reset Process (GAO, 2012, Figure 1)



Source: GAO analysis of DOD data.

In-Theater Maintenance, Repair, and Overhaul: The Theater Sustainment Stocks (TSS) and the Theatre Provided Equipment (TPE) Initiatives

One disadvantage of the traditional process is that performing repairs in the United States requires transporting the equipment round trip to and from the United States. However, this equipment could be repaired in-theater using the three advanced technologies. The Army initiated two equipment reuse efforts, the Theater Sustainment Stocks (TSS) and Theater Provided Equipment (TPE) in an attempt to increase operational availability and reduce costs. The Theater Sustainment Stocks (TSS) retain an inventory of more than 400 types of vehicles and other equipment in theater for deployment with arriving units. The Marine Corps has a similar program named Forward In-Stores. In the Army case, this portion of the Mountain typically requires repairs to be operational, and those repairs often do not return the equipment to full capability. For example, the GAO found that less than 7% of a cross-section of ground vehicles in TSS were fully mission capable (Soltis, 2006). Increased in-theater repair capability can increase the operational availability of TSS equipment.

Since its initiation in 2003, the Theater Provided Equipment[2] (TPE) initiative takes force-protection equipment from forces returning to the United States while the equipment is still in theater instead of shipping it back with the units that brought it into the theater. The program transfers the equipment to incoming units. Transfers typically happen at forward stations and departing units are expected to maintain equipment to full mission capabilities. Almost 75% of the Army's trucks in Iraq are in the TPE pool (CBO, 2007). While increasing operational availability of equipment to users and saving shipping costs, the TSS and TPE programs, as currently implemented, prevent depot level MRO such as overhauls. This can require more and more expensive repairs later. Improved MRO in-theater or repairs at forward stations can increase the effectiveness of TPE.

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[2] Theater Provided Equipment was referred to as "stay behind equipment" until 2005.

Three Advanced Technologies

Three advanced technologies, that is, three-dimensional laser scanning technologies (3DST), additive manufacturing (AM), and product lifecycle management (PLM), have the potential to significantly improve the processes used to shrink the Mountain. The following sections provide an overview of these technologies based on a prior study by Housel, Hom, Ford, and Mun (2015).

Three-Dimensional Laser Scanning Technologies

Three-dimensional laser scanning technologies (3DST) have been used to achieve significant cost savings, optimize maintenance schedules, increase quality, improve safety, and reduce re-work. Commercial applications range from maritime and space applications to manufacturing and production. According to industry analysts, the industry’s growth is fueled by the growing recognition that 3D aids in the design, fabrication, construction, operations, and maintenance processes.

Laser scanners use infrared laser technology to produce exceedingly detailed three-dimensional images of complex environments and geometries in only a few minutes. Millions of discrete measurements are captured in every scan. The resulting images, a “point cloud,” are millions of 3D measurement points. A complete project may contain hundreds of millions or even billions of points, recreating the complex spatial relationships of the 3D environment. Three-dimensional scanners can be used to get complete or partial 3D measurements of any physical object without any contact with the physical object.

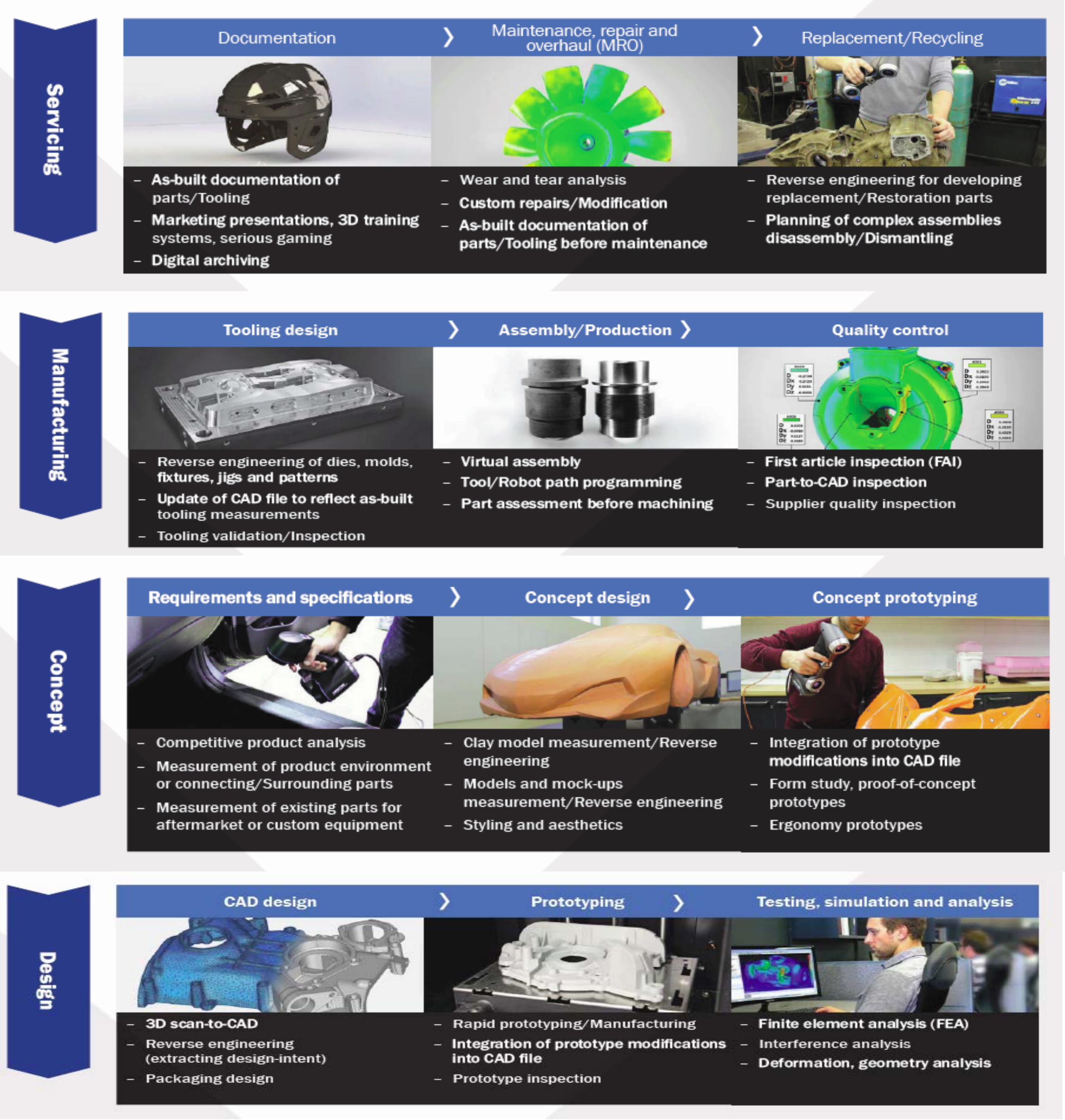
Often used by offshore oil and gas companies to construct and repair oil rigs, 3DST is very effective at documenting oil platforms and refineries to assist in engineering, maintenance, and planning processes. The aerospace and automotive industries have used 3DST for retrofitting floors and measuring parts for accurate fit. The following are other industries using the technology:

- ***Law Enforcement.*** Used in crime scene documentation, forensics, and accident reconstruction.

- ***Architectural and Civil Engineering.*** Used to capture as-built documentation of existing buildings and structures such as bridges and provides architects and contractors with exact dimensions. Building Information Models (BIM) can be developed to retrofit projects.
- ***Asset and Facility Management/Documentation***. Three-dimensional documentation of complex factory and plant installations provide users with very precise 3D CAD data for use in facility management, maintenance, and asset documentation.
- ***Surveying.*** Used to complement or replace traditional tools such as total stations to fully capture manmade or natural objects for volume calculations, as-built surveys, and topographic surveys (Faro, 2014).

Example applications of 3DST in PLM include the manufacturing, servicing, design, and concept areas as shown in Figure 4.

Figure 4. Actual and Potential Applications of 3D Scanning



Servicing

Documentation
- As-built documentation of parts/Tooling
- Marketing presentations, 3D training systems, serious gaming
- Digital archiving

Maintenance, repair and overhaul (MRO)
- Wear and tear analysis
- Custom repairs/Modification
- As-built documentation of parts/Tooling before maintenance

Replacement/Recycling
- Reverse engineering for developing replacement/Restoration parts
- Planning of complex assemblies disassembly/Dismantling

Manufacturing

Tooling design
- Reverse engineering of dies, molds, fixtures, jigs and patterns
- Update of CAD file to reflect as-built tooling measurements
- Tooling validation/Inspection

Assembly/Production
- Virtual assembly
- Tool/Robot path programming
- Part assessment before machining

Quality control
- First article inspection (FAI)
- Part-to-CAD inspection
- Supplier quality inspection

Concept

Requirements and specifications
- Competitive product analysis
- Measurement of product environment or connecting/Surrounding parts
- Measurement of existing parts for aftermarket or custom equipment

Concept design
- Clay model measurement/Reverse engineering
- Models and mock-ups measurement/Reverse engineering
- Styling and aesthetics

Concept prototyping
- Integration of prototype modifications into CAD file
- Form study, proof-of-concept prototypes
- Ergonomy prototypes

Design

CAD design
- 3D scan-to-CAD
- Reverse engineering (extracting design-intent)
- Packaging design

Prototyping
- Rapid prototyping/Manufacturing
- Integration of prototype modifications into CAD file
- Prototype inspection

Testing, simulation and analysis
- Finite element analysis (FEA)
- Interference analysis
- Deformation, geometry analysis

Source: Creaform, 2015

Three-Dimensional Laser Scanning Technologies in the Navy

Ship Check Data Capture 2005

Recognizing the potential of new technologies on the ship check process on the U.S. shipping industry, the Navy funded the Ship Check Data Capture project in 2005. Laser scanning, close-range photogrammetry and other technologies capturing as-built ship conditions in digital format to create 3D electronic models were evaluated. The project's goals were to determine potential technology synergies producing cost effective solutions and prototype a ship check data capture process that could be used by the U.S. shipbuilding industry. It was also anticipated that archived digital data would provide a cost-effective solution to the lifecycle cost management of ships.

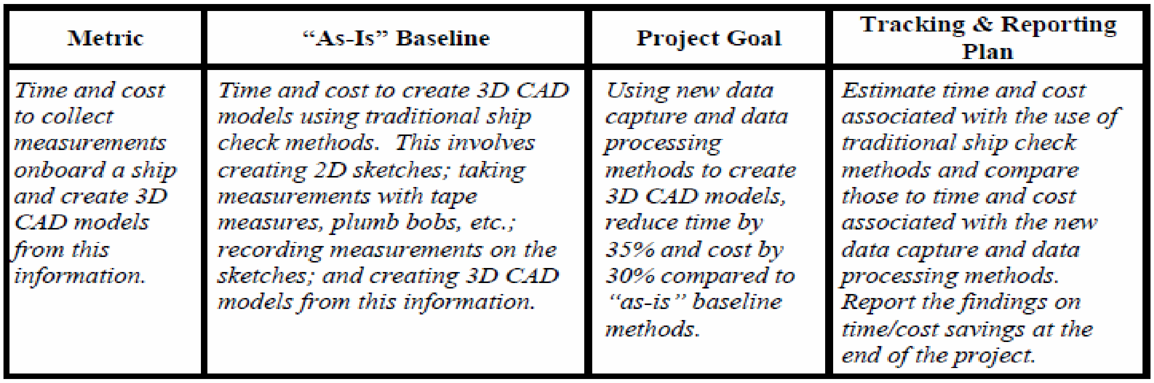
Specific benefits from the software and hardware tested include the following:

- Creation of as-built 3D models and validation of as-built models to design models
- Reduction of costly design changes, improved design capability
- Reduced construction rework
- Accurate factory-fabricate in lieu of field-fabricate
- Reduced ship check costs: fewer days, fewer personnel
- Elimination of return visits to the ship for missed measurements
- Obtaining measurements which are difficult or unsafe for human reach

Initial results were so encouraging from this project that a nine month follow-on project was awarded by the NSRP in 2006. The follow-on project evaluated the ship check process developed in the FY05 project and refined the process for the U.S. shipbuilding and repair industry using available Commercial-Off-The-Shelf (COTS) technology. In this follow-up project, the team conducted a ship check onboard a surface ship at Bender Shipbuilding & Repair Company and conducted work onboard SSGN 729 to validate the data accuracy/repeatability of the SSGN 729 ship check data collected from the FY05 project.

Performance improvement metrics were developed and tracked to compare the “as-is” practice with anticipated project results, as shown in Table 1. This project reported the cost/time savings metrics associated with post processing the ship check data into 3D CAD models compared to creating CAD models using the traditional ship check method with tape measures.

Table 1. Project Performance Improvement Measurements



Metric	“As-Is” Baseline	Project Goal	Tracking & Reporting Plan
Time and cost to collect measurements onboard a ship and create 3D CAD models from this information.	*Time and cost to create 3D CAD models using traditional ship check methods. This involves creating 2D sketches; taking measurements with tape measures, plumb bobs, etc.; recording measurements on the sketches; and creating 3D CAD models from this information.*	*Using new data capture and data processing methods to create 3D CAD models, reduce time by 35% and cost by 30% compared to “as-is” baseline methods.*	*Estimate time and cost associated with the use of traditional ship check methods and compare those to time and cost associated with the new data capture and data processing methods. Report the findings on time/cost savings at the end of the project.*

Source: NSRP 2007

Estimated cost savings of 37% and time savings of 39% were realized for ship check data capture/post processing with the available COTS laser scanning technology hardware and software tools results when compared to traditional ship checks using tape measures. The project team concluded that the technology (hardware/software) was mature enough to support the ship check process. Laser scanners were found to provide a cost effective method to collect as-built data during ship checks as compared to traditional methods. Three-dimensional laser scanning provided time and cost savings, and can be applied to the shipbuilding industry.

3D Scanning in the Navy

In 2005, 3D laser scanning services were used for ship check of a three-story hangar bay on the USS *Abraham Lincoln* (CVN 72). Scanning the HVAC, piping, fuel storage tanks, and other structures allowed shipyard engineers to conduct multi-discipline “what-if” scenarios to avoid clashes in the installation of a new deck. Hundreds of hours in labor were saved with scanning versus the traditional methods.

Three-dimensional laser scanning captured data at up to 2000 points per second and has a range accuracy of 0.2 inches at 55 feet.

Three-dimensional laser scanning technology was used to assess damage to the USS *San Francisco* (SSN 711) after it collided at high speed with an undersea mountain 350 miles south of Guam. Three-dimensional laser scanning was used to evaluate the damaged areas of the submarine’s bow. In this case, scanning was invaluable for determining the ship's centerline and collecting empirical data about torpedo tube deformation.

The Naval Undersea Warfare Center (NUWC) began using laser scanning to reverse engineer components with complex geometries in order to enable competitive bidding in 2007. In the past, the Navy did not have sufficient documentation from the Original Equipment Manufacturer (OEM) to competitively procure replacement components which resulted in purchasing expensive replacements from the OEM. The Navy saved $250,000 by purchasing parts produced with laser scanning through competitive bidding. Additionally, the time required to reverse engineer a typical component, including both measurement and modeling time, was reduced from 100 hours to 42 hours with a laser scanner.

Additive Manufacturing (Based on Housel et al., 2015)

Lu, Li, and Tian (2015) contrast additive manufacturing (AM) with equivalent and subtractive forms of manufacturing. Equivalent manufacturing uses the same amount of material to create the product as is in the final product. The mass change during equivalent manufacturing is zero. Casting, forging, and soldering are examples of equivalent manufacturing. Subtractive manufacturing removes material during manufacturing. The mass change during subtractive manufacturing is negative. Milling, turning, and grinding are examples of subtractive manufacturing. In contrast, AM adds material during manufacturing. The mass change in additive manufacturing is positive. Stereolithography is an example of additive manufacturing.

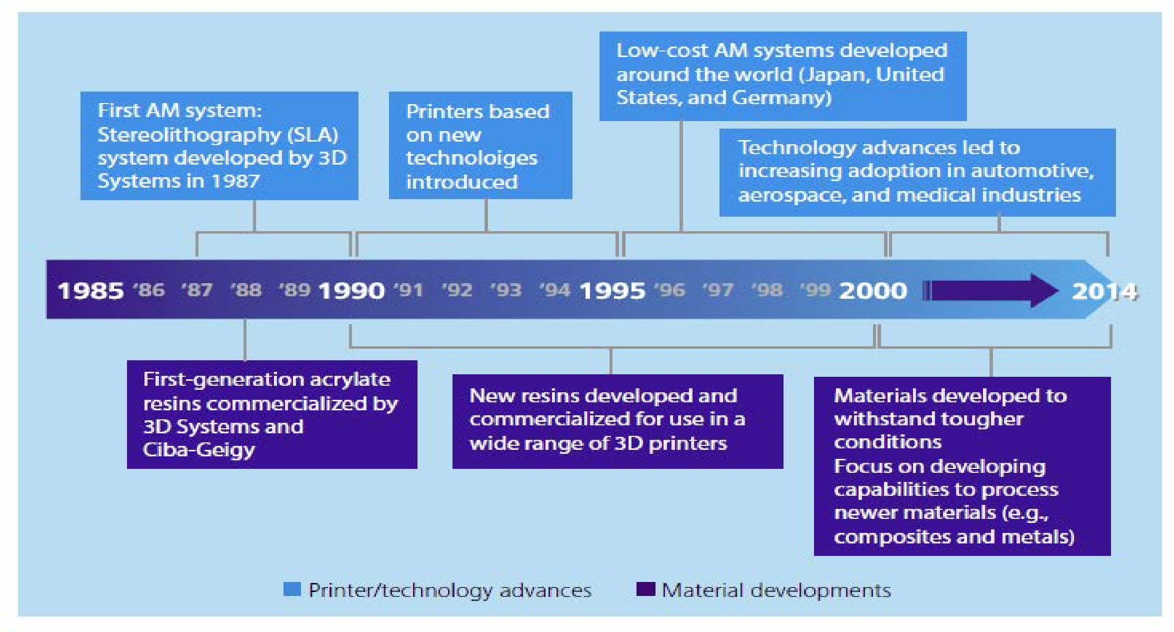
The American National Standards Institute defines additive manufacturing as the "process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM, 2013). Additive manufacturing is also commonly referred to as 3D printing. AM differs radically from the currently dominant manufacturing methodologies. Most current methods use subtractive processes (e.g., machining), but AM builds a 3D object by gradually adding successive layers of material that are laid down exactly in their final location. AM does this by fabricating objects directly from 3D computer-aided design (3D CAD) models. The 3D model is disaggregated into multiple horizontal layers, each of which is produced by the machine and added to the preceding layers. Additive manufacturing is often referred to as 3D printing.

AM generally involves a number of steps that move from a virtual 3D CAD model to a physical 3D object, as follows:

- **CAD:** A 3D CAD model of the target object is built in software, some times based on a 3D scanned image of the target generated with 3DST. The 3D CAD model determines only the geometry of the target object. Three-dimensional laser scanning can be used to create the model.
- **Conversion to files for manufacturing:** The CAD model cannot be used directly by AM machines; it must be converted to a format usable by the specific AM technology (e.g., stereolithography) being used. These files describe the external closed surfaces of the original CAD model and forms a basis for calculation of the layers used in manufacturing. The model approximates surfaces of the model with a series of triangular facets.
- **Revision of manufacturing files:** The manufacturing files must be manipulated before manufacturing. For example, multiple objects may be manufactured simultaneously from the same file, requiring that the files of the objects be integrated.
- **Machine setup:** AM machines must be set up to accommodate specific materials, layer thicknesses, and timing.
- **Build:** Although all AM machines follow the layer-by-layer fabrication process, they utilize different techniques and technologies. For example, some of them use a high-power laser beam to melt a very fine metal powder in order to form a thin layer, while others use UV light to solidify a specific kind of liquid polymer, called *photopolymer*.
- **Post-process:** Post-processing may be required due to the need to cure photopolymers.

The first additive manufacturing system was created in the early 1980s when Charles Hull invented stereolithography (SLA), a printing process that enabled a tangible 3D object to be created from digital data. The technology was then used to create a 3D model from a picture and allows users to test a design before investing in a larger manufacturing program. Since then, AM has evolved to include at least 13 different sub-technologies grouped into seven distinct process types. Figure 5 shows the evolution of additive manufacturing technology.

Figure 5. Evolution of AM Technology, 1985–2014



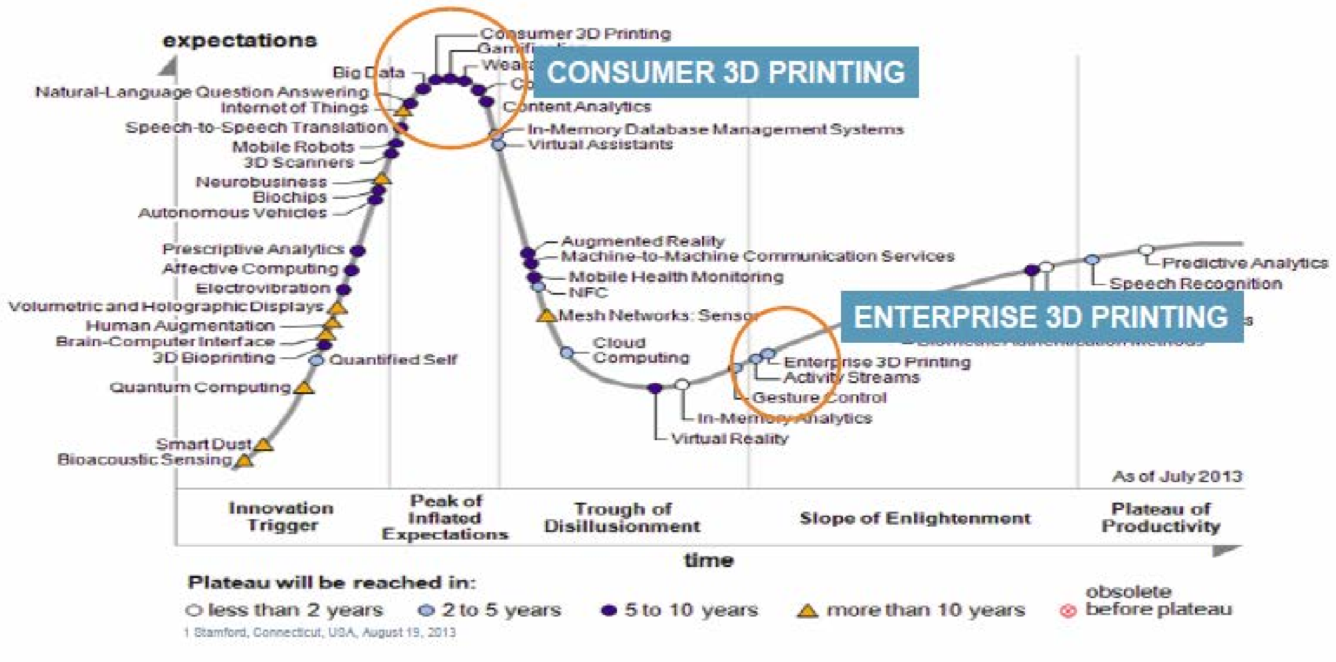
(Deloitte,2015)

According to the Gartner Group, consumer adoption of 3D laser printing will take several years (as seen in Figure 6). Gartner defines five key phases of a technology's life cycle:

- **Technology Trigger.** A new technology triggers excitement for the technology. There are early proof-of-concept stories and media interest, however, no usable products and un-confirmed commercial viability at this phase.

- **Peak of Inflated Expectations.** There are several early successes, in conjunction with several failures. Although some companies adopt the technology early, many do not.
- **Trough of Disillusionment.** Interest lessens as implementations fail to deliver. An industry shakeout occurs.
- **Slope of Enlightenment.** The technology's benefits become more understood as second- and third-generation products emerge.
- **Plateau of Productivity.** Mainstream adoption of the technology.

Figure 6. Gartner's 2013 Hype Cycle for Emerging Technologies



Source: Gartner 2013

AM is already a staple in many manufacturing processes and is increasingly being used across a number of industries, including aviation, automobile, and healthcare. Lockheed Martin estimates that some complex satellite components can be produced 48% cheaper and 43% faster with 3D. Production costs could be reduced by as much as 80%. Boeing has installed environmental control system ducting made by AM for its commercial and military aircraft for many years; tens of thousands of AM parts are flying on 16 different production aircraft (commercial and military; Wohlers, 2014). GE Aviation will be using AM to manufacture more than 30,000 fuel nozzles annually for its new LEAP engine starting in 2015. Consolidating 18 parts into one, the new design is 25% lighter and five times more durable than the previous fuel nozzle.

In the automotive industry, Ford Motor Co. uses 3D printing in several areas, including the tooling used to create production parts and to build intake manifold prototypes that can be tested for up to 100,000-mile cycles. With traditional manufacturing methods, it would take four months and cost $500,000 to build while a 3D-printed manifold prototype costs $3,000 to build over four days.

Additive Manufacturing in the Armed Forces

The U.S. Navy has supported research into 3D printing for more than 20 years and has approximately 70 additive manufacturing projects underway at dozens of different locations. Table 2 summarizes benefits achieved for several completed projects. In addition, one of the active Navy Manufacturing Technology (ManTech) Program projects active in FY14 was the “Non-Destructive Inspection for Electron-Beam Additive Manufacturing of Titanium.” In this project, the emerging AM technology of Electron Beam Direct Manufacturing (EBDM) process was evaluated for fabrication of several F-35 Joint Strike Fighter (JSF) components. EBDM is a technology that is considered vital to improving the affordability, reducing lead time, and reducing industrial shortfalls inherent in traditional manufacturing technologies. In this Navy Metalworking Center (NMC) ManTech project, an Integrated Project Team (IPT) evaluated the effectiveness of traditional and advanced non-destructive inspection (NDI) techniques, including computed tomography (CT) scanning, traditional radiography, standard hand-held ultrasonic, and phased array ultrasonic inspection methods, to establish standardized NDI processes and procedures for production. According to the Office of Naval Research, studies have shown that EBDM technology has the potential to reduce per-part manufacturing costs by 35% to 60% when compared to the costs to manufacture complex-shaped parts with traditional manufacturing approaches (ONR, 2015). Product lead time might also be reduced by as much as 80%.

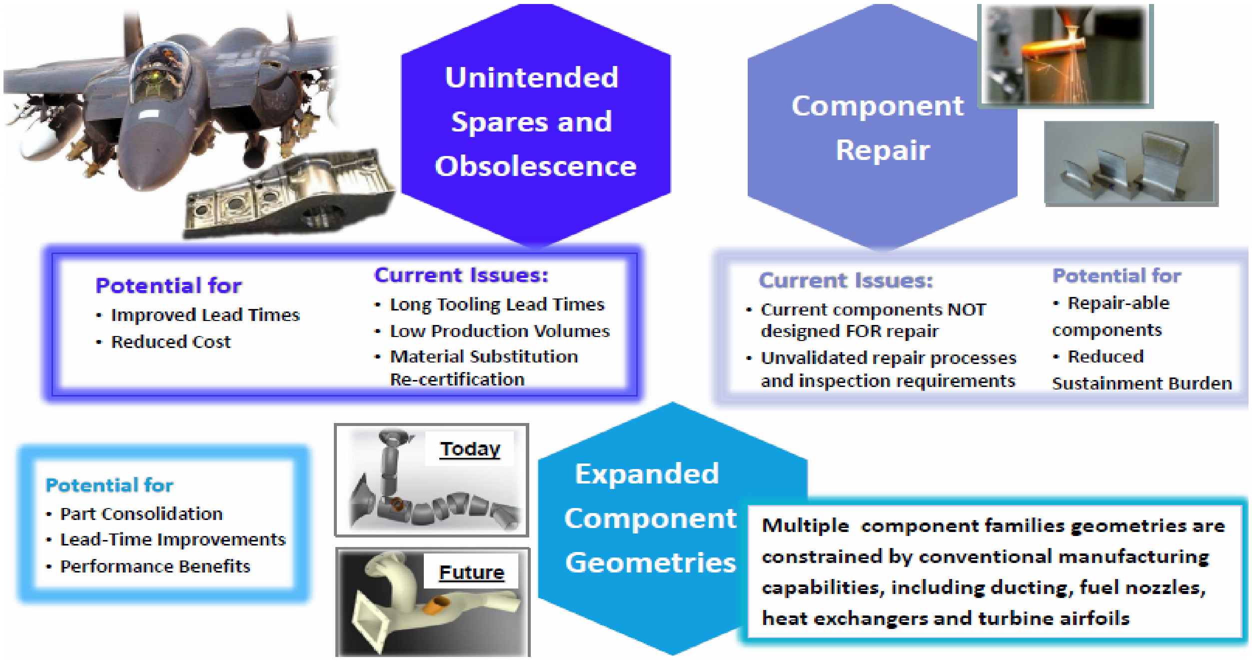
Table 2. Example AM Projects and Benefits

	Rapid Manufacturing & Repair: Casting Cores	RARE Parts Program: Part Vacuum Rotor Weapon System Submarines	ManTech Data Link Systems
Cost & Time Savings	$4K & 4 weeks	$20K & 30 weeks	• Reduced unit cost of Mini Data Link Diplexer from ~$20,000 to ~$2,000 each • Reduced lead time from 13 months to 3 months • Approx. 65% cost savings
Problem/ Challenge	• Providing low quantity castings for fleet needs	• Vacuum Rotor: Part can be hard to get. • Cost is $19K, lead time 48 weeks	• Warfighter needs real time networked data in theater. • However, cost grows as bandwidths become more crowded. • Data link systems found in Unmanned Arial Vehicles (i.e., Predator, Global Hawk, Hunter) are expensive, have long lead times due to exotic materials, and require extensive skilled labor with long cycle times.
Solutions/ Results	• System for printing sand casting molds and cores: skips cost and lead time associated with making a pattern to pack sand around	• Part reverse engineered and CAD model created by TRF-King's Bay. Mold modeled at NUWC-Keyport, and mold will be poured by Naval Foundry & Propeller Center (NFPC) • Printed mold using Ex One S15 system, cast parts at local foundry • Cost $14K, lead time 8 weeks	• Air Force ManTech developed and produced a tuneless diplexer using additive manufacturing to reduce material waste, cycle time, cost, and to increase yield • Utilized highly-developed software simulation and advanced manufacturing techniques to create Advanced Tuneless Diplexer that delivers superior performance at significantly reduced cost • Implemented the following manufacturing improvements into new Mini Data Link product to improve overall data link lead time and cost: –Replaced complex precision machined parts with inexpensive die cast components –Eliminated gold plating, tuning, and re-tuning –Incorporated automated test to assess twenty units at a time • AFRL ManTech investment of $5.4M
Benefit/ Impact	• Costs: Slight cost decrease • Time: Substantially reduces lead time • Weapon System: Any system that uses castings	• Costs: $20K savings per year based on 4 units annually • Time: 30 week lead time reduction—better suits emergent needs • Weapon System: Vacuum / priming pump used on subs	• Provides Warfighter with affordable, capable, real time networked data • Increased performance and reliability of diplexer by reducing manufacturing variability

Sources: Root 2014

The U.S. Army deployed its first mobile 3D printing laboratory in July 2012 in Afghanistan inside a shipping container that is capable of being carried by helicopter. Figure 7 highlights how additive manufacturing can be used in maintenance activities.

Figure 7. Army's Additive Manufacturing Opportunities



Source: Naguy 2014, pg. 3

Product Lifecycle Management (Based on Housel et al., 2015)

The meaning of Product Lifecycle Management (PLM) continues to evolve. It has been defined as an "integrated, information-driven approach comprised of people, processes/practices, and technology, to all aspects of a product's life, from its design through manufacture, deployment and maintenance—culminating in the product's removal from service and final disposal. By trading product information for wasted time, energy, and material across the entire organization and into the supply chain, PLM drives the next generation of lean thinking" (Greives, 2006). In another definition by CIMdata (n.d.),

> PLM is a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise, and

> spanning from product concept to end of life-integrating people, processes, business systems, and information. PLM forms the product information backbone for a company and its extended enterprise.

Finally, the Gartner Group defines “PLM is a discipline for guiding products and product portfolios from ideas through retirement to create the most value for businesses, their partners, and their customers.” Although definitions differ, there is agreement that PLM is a systematic approach to managing the series of changes from its design and development to its ultimate retirement or disposal.

PLM has been used by the automotive, aerospace, and other industries that build very large, very complex products and systems. It was designed to provide stakeholders with current views of every product throughout its lifecycle to facilitate decision-making and corrective actions if necessary.

A wide range of industries using PLM are finding that 3DLS is becoming a critical tool to link the gap between physical objects in the real world and in the digital design world. The aerospace, automotive, consumer products, manufacturing, and heavy industries all have benefited from faster time to market, improved quality, and reduced warehousing costs with 3D scanning.

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Potential Process Options to Shrink the Mountain

Current Capabilities and Forecasted Developments of 3D Scanning Technologies, Additive Manufacturing, and Product Lifecycle Management

A general review of the current and future capabilities of each technology will provide the basis for forecasting how those technologies might be used to shrink the Mountain. The following review of how they might be used immediately and in the future as they add new functionalities is necessary to make reasonable forecasts about how much cost they can reduce over time.

3D Scanning Technologies

Current capabilities and uses of 3D scanning technology include the following:

- Tabletop scanning and mapping of fixed objects
- Portable, handheld (no mechanical fix to the scanned object) mapping of free form surfaces (Allard, Lavoie, & Fraser, 2013)
- Translation from point cloud collected by scanning to CAD files for design and manufacturing

Potential future capabilities of 3D scanning technology include the following:

- Scanning technologies integrated with other sensing technologies
- Smart scanning software that automatically diagnoses damage based on scanned data
- Scanners communicating directly with repair facilities
- Scanners communicating directly with manufacturing equipment for automated manufacturing of parts based on damage assessment
- User-based damage assessment such as units carrying portable 3D scanners for equipment diagnostics

Future applications of 3DST within the DoD can include the use of portable (tabletop-sized) and very portable (handheld) scanners by in-theater repair facilities and at forward stations by repair personnel and equipment users for on-site damage and in-theater assessment and diagnosis. Damage assessment software may be developed to analyze scanned data (e.g., whether actual deviation from design shapes prevents full capability) and thereby speed diagnosis. Three-dimensional scanning technology can be integrated with AM and automated to speed the creation of replacement parts. The technology may eventually be used to sense component conditions while in use and collect user experience data for use in real time conditions assessment and repair.

Additive Manufacturing

Current capabilities and uses of additive manufacturing include the following:

- Translation from CAD drawings to manufacturing files for use by AM machines
- Making molds for casting parts (Lu et al., 2015)
- Manufacturing with most materials (Lu et al., 2015)
- Manufacturing complex shaped parts (Lu et al., 2015)
- Manufacturing small numbers of parts more cheaply that traditional manufacturing methods (Thomas & Gilbert, 2014)
- Reduction in size of equipment required compared to many traditional manufacturing methods (Lu et al., 2015), allowing more localized manufacturing

Potential future capabilities of additive manufacturing include the following:

- Redesign the shapes of parts to exploit additive manufacturing advantages for parts such as heat exchangers and lightweight structures (e.g., drone parts; Lu et al., 2015) and custom fitting protective gear (Earls & Baya, 2014).
- Goal-driven computer design of parts that optimizes designs for weight, strength, etc. (Smith, 2015).
- Integrate additive manufacturing into design of part characteristics (Lu et al., 2015). AM can be used to control the internal stresses within a part. Therefore single parts will, for example, be designed to be stronger at the locations of larger loads.
- Integral design and manufacturing of multiple-material parts (Lu et al., 2015; Smith, 2015)—e.g., alternating layers of interacting materials with different characteristics such as stiffness and density (Earls & Baya, 2014).

- Manufacturing at the micro and nano scales of objects such as miniature transducers (Lu et al., 2015; Smith, 2015).
- Combination and integration of AM, equivalent, and subtractive manufacturing methods for the manufacturing of parts such as prototypes, molds, electrodes, and casting patterns (Lu et al., 2015).
- Design and use of high-performance alloys such as for high-temperature conditions (Lu et al., 2015).
- Intelligent manufacturing equipment which senses and responds to manufacturing conditions in real time (Lu et al., 2015).
- Consolidation of many components such as sensors, batteries, and electronics into fewer, more complex components, subsystems, and systems. For example, printing circuits, antennas, and RFID tags into products (Earls & Baya, 2014) such as helmets, boots, and clothing (Anusci, 2015)
- Manufacturing of complete subsystems such as small drone wings (Earls & Baya, 2014).
- Small scale and portable manufacturing that allows on-site parts and equipment manufacturing (Smith, 2015).
- Four-dimensional printing in which products change over time in response to conditions, such as for self-assembly, increased strength when in the presence of moisture or a specified temperature (Smith, 2015).

Future applications of AM technologies within the DoD can include their widespread use for making single or small batches of replacement parts from basic materials, manufacturing near forward stations, integration and automation with 3DST for faster parts creation and custom parts, and component designs and manufacturing using diverse and multiple materials, integrated component manufacturing for faster and cheaper repair work, and 4D component design and manufacturing that changes with time or environmental conditions.

Product Lifecycle Management

Current capabilities of product lifecycle management include the following:

- Aggregation and storage of component-specific data
- Data sharing across user locations and time
- Component life tracking
- Inventory analytics

Potential future capabilities of product lifecycle management include the following:

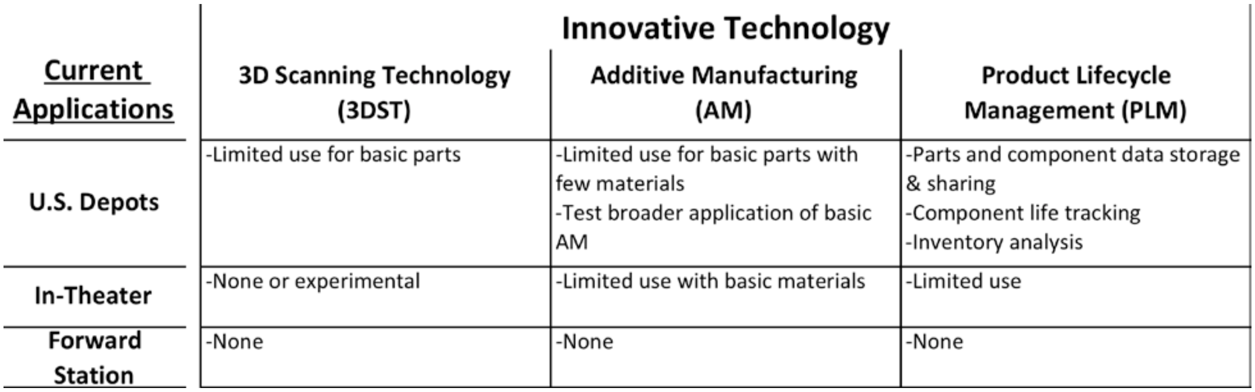
- Future applications of PLM within the DoD (Shilovitsky, 2016)
- Smart objects that send and receive data and instructions through the PLM system
- Coordination and communication among connected devices that allow manager-to-component, user-to-component, and component-to-component communication
- Automated product performance monitoring and reporting in real time
- User-experience data collection in real time and analysis for improved component design
- Smarter software that can improve repair forecasting and planning by predicting demand

Future applications of PLM within the DoD can include automated inventory management, repair demand forecasting and planning based on parts conditions, integration of manufacturing across subtractive, equivalent, and additive processes, and 4D component design and manufacturing that changes with time or environmental conditions, and the full integration of 3DST, manufacturing, and PLM.

Forecasted Evolutions of the Three Advanced Technologies for Shrinking the Mountain

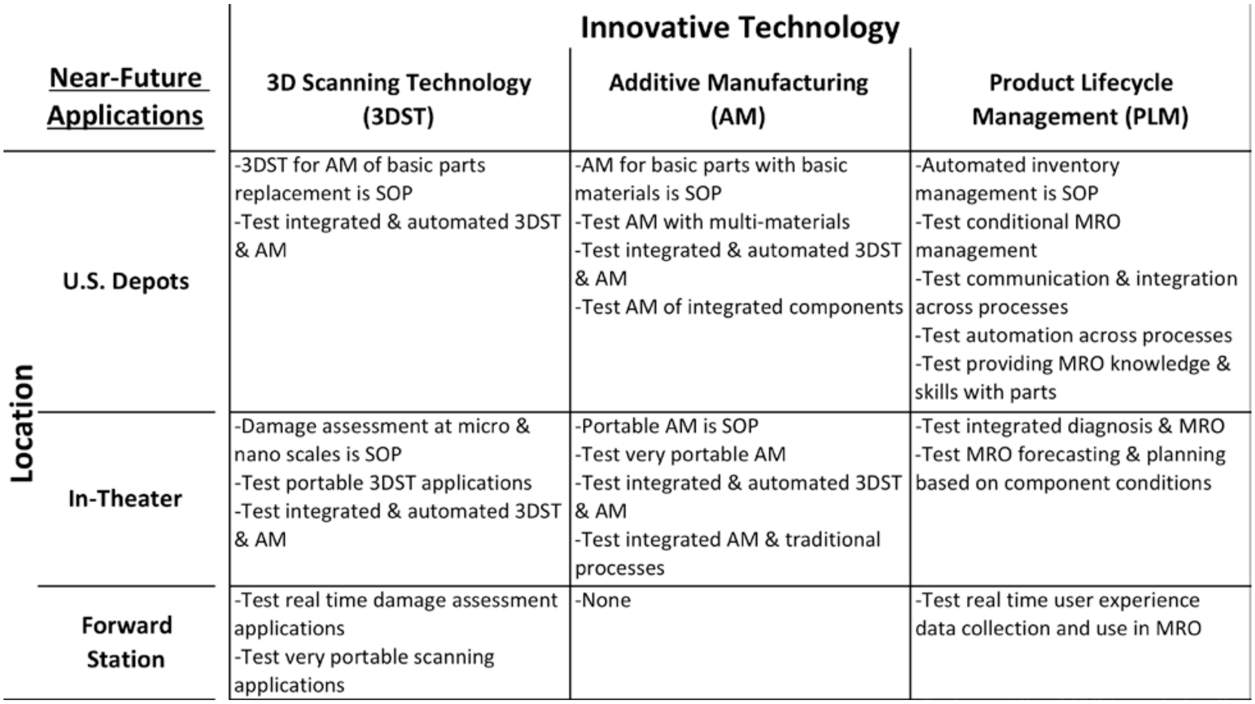
Advanced technologies uses for shrinking the Mountain are expected to differ by location, that is, whether used at forward stations, in-theater repair facilities, or at U.S. depots. Forecasted applications of each technology in these three locations were developed for three temporal scenarios: current use (Table 3), use in the near future (5–10 years; Table 4), and use in the distant future (more than 10 years; Table 5). Location vs. Technology tables with cells describe activities (e.g., maintenance, minor repair, overhaul, and diagnosis.

Table 3. Current Repair Applications of Three Advanced Technologies



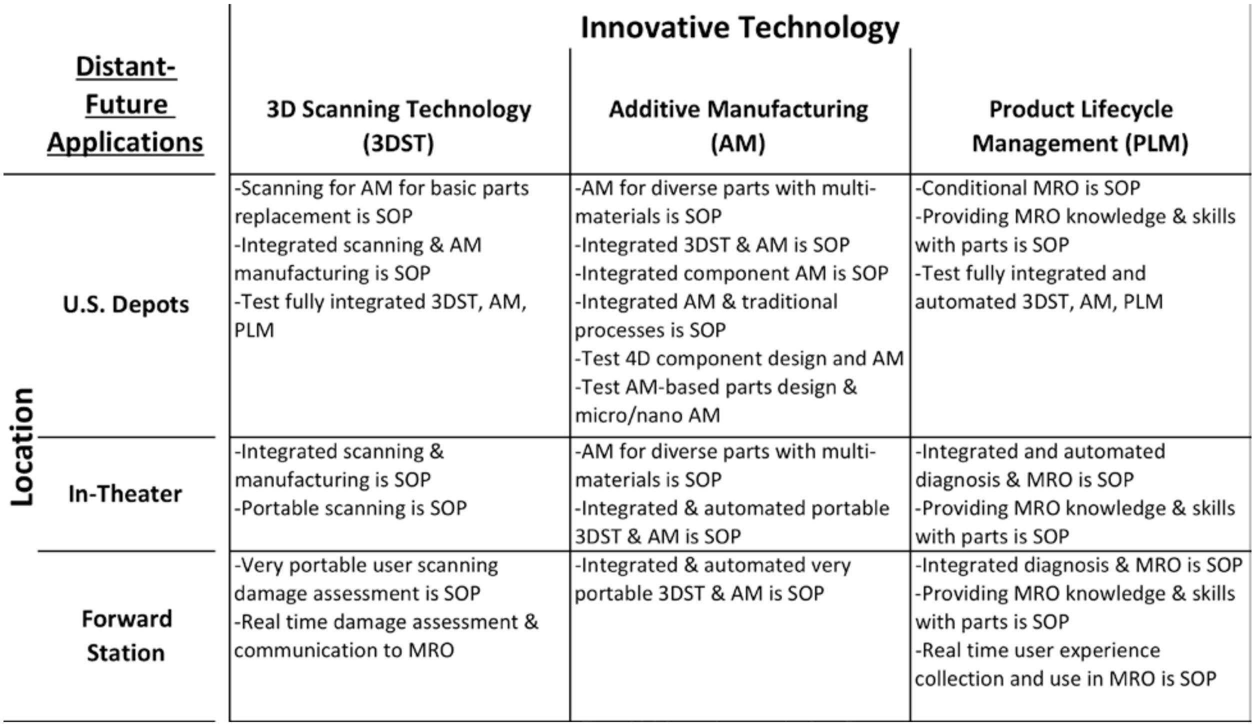
Current Applications	Innovative Technology		
	3D Scanning Technology (3DST)	Additive Manufacturing (AM)	Product Lifecycle Management (PLM)
U.S. Depots	-Limited use for basic parts	-Limited use for basic parts with few materials -Test broader application of basic AM	-Parts and component data storage & sharing -Component life tracking -Inventory analysis
In-Theater	-None or experimental	-Limited use with basic materials	-Limited use
Forward Station	-None	-None	-None

Table 4. Near-Future Repair Applications of Three Technologies



	Near-Future Applications	Innovative Technology		
		3D Scanning Technology (3DST)	Additive Manufacturing (AM)	Product Lifecycle Management (PLM)
Location	**U.S. Depots**	-3DST for AM of basic parts replacement is SOP -Test integrated & automated 3DST & AM	-AM for basic parts with basic materials is SOP -Test AM with multi-materials -Test integrated & automated 3DST & AM -Test AM of integrated components	-Automated inventory management is SOP -Test conditional MRO management -Test communication & integration across processes -Test automation across processes -Test providing MRO knowledge & skills with parts
	In-Theater	-Damage assessment at micro & nano scales is SOP -Test portable 3DST applications -Test integrated & automated 3DST & AM	-Portable AM is SOP -Test very portable AM -Test integrated & automated 3DST & AM -Test integrated AM & traditional processes	-Test integrated diagnosis & MRO -Test MRO forecasting & planning based on component conditions
	Forward Station	-Test real time damage assessment applications -Test very portable scanning applications	-None	-Test real time user experience data collection and use in MRO

Table 5. Distant-Future Repair Applications of Three Technologies



	Distant-Future Applications	**Innovative Technology**		
		3D Scanning Technology (3DST)	**Additive Manufacturing (AM)**	**Product Lifecycle Management (PLM)**
Location	**U.S. Depots**	-Scanning for AM for basic parts replacement is SOP -Integrated scanning & AM manufacturing is SOP -Test fully integrated 3DST, AM, PLM	-AM for diverse parts with multi-materials is SOP -Integrated 3DST & AM is SOP -Integrated component AM is SOP -Integrated AM & traditional processes is SOP -Test 4D component design and AM -Test AM-based parts design & micro/nano AM	-Conditional MRO is SOP -Providing MRO knowledge & skills with parts is SOP -Test fully integrated and automated 3DST, AM, PLM
	In-Theater	-Integrated scanning & manufacturing is SOP -Portable scanning is SOP	-AM for diverse parts with multi-materials is SOP -Integrated & automated portable 3DST & AM is SOP	-Integrated and automated diagnosis & MRO is SOP -Providing MRO knowledge & skills with parts is SOP
	Forward Station	-Very portable user scanning damage assessment is SOP -Real time damage assessment & communication to MRO	-Integrated & automated very portable 3DST & AM is SOP	-Integrated diagnosis & MRO is SOP -Providing MRO knowledge & skills with parts is SOP -Real time user experience collection and use in MRO is SOP

Modeling Improved Processes to Shrink the Mountain

We will use the knowledge value added methodology to structure the problem of forecasting the future value and cost reductions possible when the three technologies are in place to support shrinking the Mountain. In what follows, we will review the methodology and how it works.

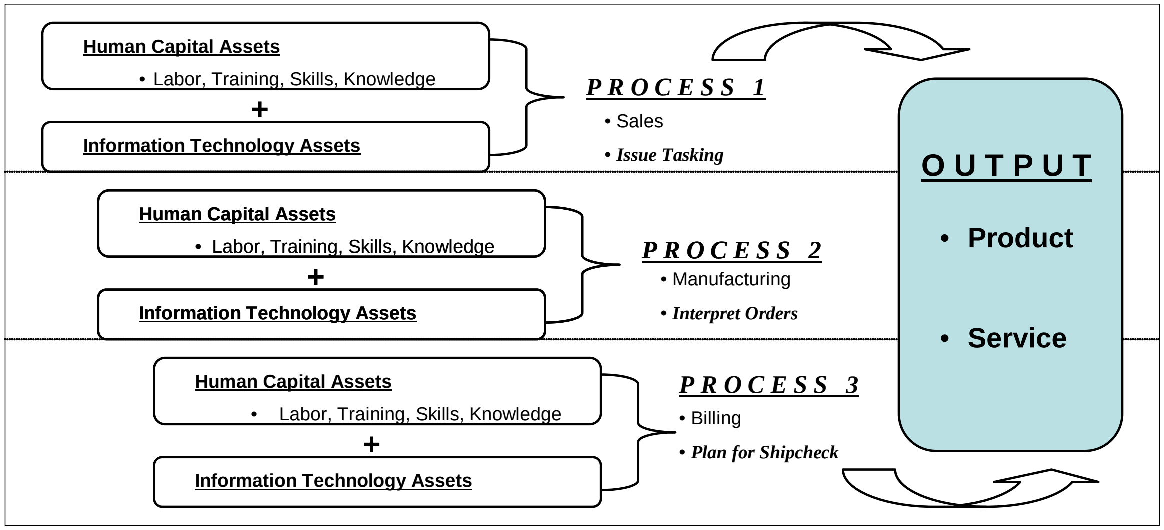
Knowledge Value Added Modeling (Based on Ford, Housel, Hom, & Mun, 2015)

In the U.S. military context, the Knowledge Value Added (KVA) methodology is a new way of approaching the problems of estimating the productivity (in terms of return on investment [ROI]) for military capabilities embedded in processes that are impacted by technology. KVA addresses the requirements of the many DoD policies and directives by providing a means to generate comparable value or benefit estimates for various processes and the technologies and people that execute them. It does this by providing a common and relatively objective means to estimate the value of new technologies as required in the

- Clinger–Cohen Act of 1996 that mandates the assessment of the cost benefits for information technology investments
- Government Accountability Office's *Assessing Risks and Returns: A Guide for Evaluating Federal Agencies' IT Investment Decision-Making*, Version 1 (February 1997) that requires that IT investments apply ROI measures
- DoD Directive 8115.01, issued October 2005, that mandates the use of performance metrics based on outputs, with ROI analysis required for all current and planned IT investments
- DoD Risk Management Guidance Defense Acquisition guidebook that requires alternatives to the traditional cost estimation be considered because legacy cost models tend not to adequately address costs associated with information systems or the risks associated with them

KVA is a methodology that describes all organizational outputs in common units. This provides a means to compare the outputs of all assets (human, machine, information technology) regardless of the aggregated outputs produced. **It monetizes the outputs of all assets, including intangible knowledge assets.** Thus, the KVA approach can provide insights about the productivity level of processes, people, and systems in terms of a ratio of common units of output (CUO). CUO produced by each asset (a measure of benefits) is divided by the cost to produce the output. By capturing the value of knowledge embedded in an organization's core processes, employees, and technology, KVA identifies the actual cost and value of people, systems, or processes. Because KVA identifies every process required to produce an output and the historical costs of those processes, unit costs and unit values of outputs, processes, functions, or services are calculated. An output is defined as the end-result of an organization's operations; it can be a product or service, as shown in Figure 8.

Figure 8. Measuring Output in the Knowledge Value Added Approach



For the purpose of this study KVA was used to measure the value added by the human capital assets (i.e., military personnel executing the processes) and the system assets (e.g., new sensor) by analyzing the processes performances. By capturing the value of knowledge embedded in systems and used by operators of the processes, KVA identified the productivity of the system-process alternatives. Because KVA identifies every process output required to produce the final aggregated output, the common unit costs and the common unit values were estimated.

The KVA methodology has been applied in more than 80 projects within the DoD, from flight scheduling applications to ship maintenance and modernization. In general, the KVA methodology was used for this study because it could

- Compare alternative approaches in terms of their relative productivity
- Allocate value and costs to common units of output
- Measure value added by the system alternatives based on the outputs each produced
- Relate outputs to cost of producing those outputs in common units

KVA quantifies value in two key productivity metrics: Return on Knowledge (ROK) and Return on Knowledge Investment (ROI). Calculations of these key metrics are shown in Table 6 KVA Metrics.

Table 6. KVA Metrics

Metric	Description	Type	Calculation
Return on Knowledge (ROK)	Basic productivity, cash-flow ratio	Function or process level performance ratio	Outputs-benefits in common units/cost to produce the output
Return on Investment (ROI)	Same as ROI at the sub-corporate or process level	Traditional investment finance ratio	(Revenue-investment cost)/investment cost

Although ROI is the traditional financial ratio, ROK identifies how a specific process converts existing knowledge into producing outputs so decision-makers can quantify costs and measure value derived from investments in human capital assets. A higher ROK signifies better utilization of knowledge assets. If IT investments do not improve the ROK value of a given process, steps must be taken to improve that process's function and performance (Figure 9).

Figure 9. Comparison of Traditional Accounting Versus Process-Based Costing

Explains what was spent

Traditional Accounting		KVA Process Costing	
Compensation	$5,000	Review Task	$1,000
Benefits/OT	1,000	Determine Op	1,000
Supplies/Materials	2,000	Input Search Function	2,500
Rent/Leases	1,000	Search/Collection	1,000
Depreciation	1,500	Target Data Acq	1,000
Admin. And Other	900	Target Data Processing	2,000
Total	**$11,400**	Format Report	600
		Quality Control Report	700
		Transmit Report	1,600
		Total	**$11,400**

Explains how it was spent

Based on the tenets of complexity theory, KVA assumes that humans and technology in organizations add value by taking inputs and changing them (measured in common units of complexity) into outputs through core processes. The amount of change an asset within a process produces can be described as a measure of value or benefit. The following are additional assumptions in KVA:

- KVA describes all process outputs in common units (e.g., using a knowledge metaphor for the descriptive language in terms of the time it takes an average employee to learn how to produce the outputs), which allows historical value and cost data to be assigned to those processes historically.
- All outputs can be described in terms of the time required for a single point of reference learner to learn to produce them.
- Learning time, a surrogate for procedural knowledge required to produce process outputs, is measured in common units of time. Consequently, units of learning time are proportionate to common units of output.
- Common units of output make it possible to compare all outputs in terms of cost per unit as well as value (e.g., price) per unit, because value (e.g., revenue) can now be assigned at the sub-organizational level.
- Once cost and revenue streams have been assigned to sub-organizational outputs, normal accounting and financial performance and profitability metrics can be applied (Rodgers & Housel, 2006; Pavlou et al., 2005; Housel & Kanevsky, 1995).

Describing processes in common units also permits, but does not require, market comparable data to be generated, particularly important for non-profits like the U.S. military. Using a market comparables approach, data from the commercial sector can be used to estimate price per common unit, allowing for revenue estimates of process outputs for non-profits. This also provides a common units basis to define benefit streams regardless of the process analyzed.

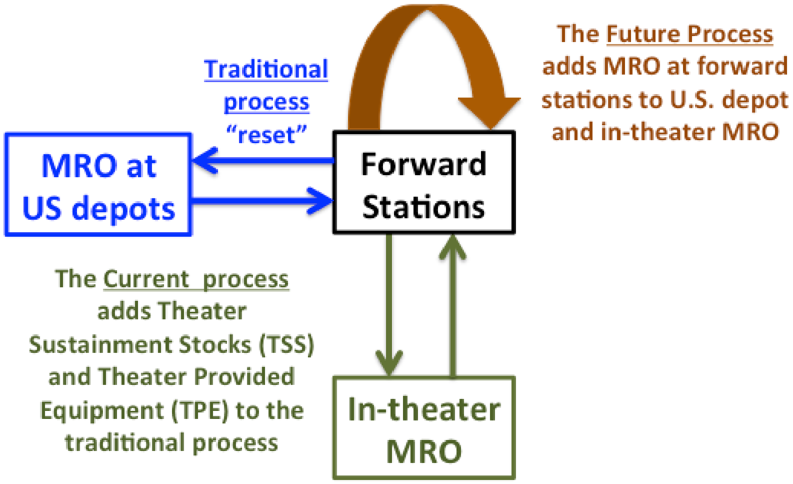
KVA differs from other nonprofit ROI models because it can allow for revenue estimates, enabling the use of traditional accounting, financial performance, and profitability measures at the sub-organizational level. KVA can rank processes or process alternatives by their relative ROIs. This assists decision-makers in identifying how much various processes or process alternatives add value.

In KVA, value is quantified in two key metrics: Return-on-Knowledge (ROK: revenue/cost) and ROI (revenue-investment cost/investment cost). The raw data from a KVA analysis can become the input into the ROI models and various forecasting techniques such as real options analysis, portfolio optimization, and Monte Carlo simulation.

Scenarios for Knowledge Value Added Modeling

The three advanced technologies investigated can help shrink the Mountain in three locations: forward stations, in-theater repair facilities, and U.S. depots and at the interactions and integration of repair work at those locations. Figure 10, Processes for Shrinking the Mountain, illustrates the repair process pathways modeled. In what follows, four scenarios were developed that demonstrated the potential cost/benefits of using the three technologies to shrink the Mountain at these three locations.

Figure 10. Processes for Shrinking the Mountain



Four advanced technology adoption and use scenarios were developed based on these pathways for modeling the abilities of the three technologies to improve the shrinking of the mountain:

- **The As-Was Scenario** reflects the traditional repair processes, in which
    - all equipment is retrograded from forward stations to U.S. depots, where it is diagnosed, repaired, and overhauled. The equipment is returned to forward stations.
- **The As-Is Scenario** reflects the current processes, which uses the traditional process for some equipment but created Theater Sustainment Stocks (TSS) to provide Theater Provided Equipment (TPE) and in-theater MRO and apply the near-future evolution of the three advanced technologies (see Table 7 in next section).
- **The To-Be Scenario** reflects near-future (5–10 years) processes, which will use the traditional processes for some equipment, Theater Sustainment Stocks (TSS) to provide Theater Provided Equipment (TPE) and in-theater repairs, and forward station repairs for some equipment, using a near-future evolution of the three advanced technologies (see Table 7 in next section).
- **The Radical To-Be Scenario** reflects distant-future (more than 10 years) processes, in which all vehicles are diagnosed twice per year, mostly at forward stations and no diagnosis is done at U.S. depots. Simple repairs are performed at forward stations and complex repairs are performed at in-theater facilities. Overhauls are performed at both in-theater facilities and at U.S. depots.

The models were built using the up-armored HMMWV as an example from which extrapolations can be derived to represent the percentage cost/benefits of shrinking the Mountain. This vehicle was chose because of the relatively large quantity (23,800), their high use in operations (essentially 100% of fleet in Iraq and Afghanistan), and the availability of data. Six variables were used to describe the differences among the four scenarios in the quantitative KVA model, as follows:

- **The number of vehicles that the process was performed on each year at which locations (forward station, in-theater facility, U.S. depot):** For each of the scenarios estimates were made of the fractions of vehicles requiring repair, requiring overhaul, and the fractions of those repairs and overhauls performed at forward station, in-theater, and at U.S. depots. In general, work moved from U.S. depots into in-theater facilities and some then to forward stations over time.
- **Number of times process performed each year per vehicle:** The process frequency for diagnosis and repair at forward stations begins at zero and increases as technology provides means for performing these processes in increasingly difficult circumstances.
- **The average number of employees that performed the process:** In general the average number of employees required to perform a task decreased with the application of advanced technologies.
- **The average time required to complete the process on a single vehicle:** The average time required to complete a process decreased with the application of advanced technologies.
- **The fraction of the process that is performed using the advanced technologies:** This fraction increased from the traditional to the current, to the near-future scenarios and was largest for the effected processes in the distant future scenario.
- **The cost of the advanced technologies:** The cost of the advanced technologies is partially based on the fraction of automation based on the assumption that partial automation would occur with technology uses as some locations but not others, allowing costs to be controlled.

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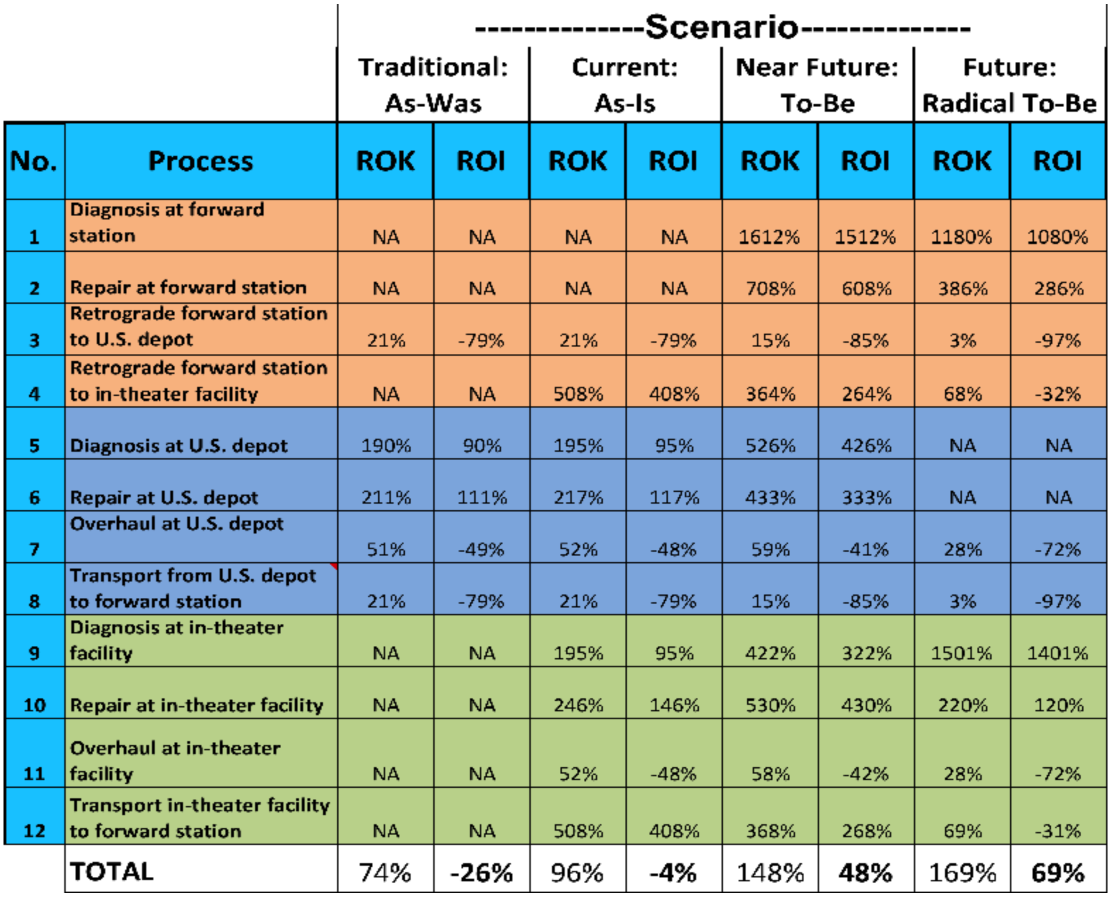
Results

Returns on Knowledge and Returns on Investment

Table 7 shows the simulated Returns on Knowledge (ROK) and Returns on Investment (ROI) of the four scenarios described in the Scenarios for Knowledge Value Added Modeling section above.

Table 7. Returns of Simulated Scenarios of Repair of Army's HMMWV Fleet[3]



		--------------Scenario--------------							
		Traditional: As-Was		Current: As-Is		Near Future: To-Be		Future: Radical To-Be	
No.	**Process**	**ROK**	**ROI**	**ROK**	**ROI**	**ROK**	**ROI**	**ROK**	**ROI**
1	Diagnosis at forward station	NA	NA	NA	NA	1612%	1512%	1180%	1080%
2	Repair at forward station	NA	NA	NA	NA	708%	608%	386%	286%
3	Retrograde forward station to U.S. depot	21%	-79%	21%	-79%	15%	-85%	3%	-97%
4	Retrograde forward station to in-theater facility	NA	NA	508%	408%	364%	264%	68%	-32%
5	Diagnosis at U.S. depot	190%	90%	195%	95%	526%	426%	NA	NA
6	Repair at U.S. depot	211%	111%	217%	117%	433%	333%	NA	NA
7	Overhaul at U.S. depot	51%	-49%	52%	-48%	59%	-41%	28%	-72%
8	Transport from U.S. depot to forward station	21%	-79%	21%	-79%	15%	-85%	3%	-97%
9	Diagnosis at in-theater facility	NA	NA	195%	95%	422%	322%	1501%	1401%
10	Repair at in-theater facility	NA	NA	246%	146%	530%	430%	220%	120%
11	Overhaul at in-theater facility	NA	NA	52%	-48%	58%	-42%	28%	-72%
12	Transport in-theater facility to forward station	NA	NA	508%	408%	368%	268%	69%	-31%
	TOTAL	74%	**-26%**	96%	**-4%**	148%	**48%**	169%	**69%**

Table 7 also identifies processes that benefit more or less relative to each other. The table shows that the diagnosis process, whether performed at forward stations (process #1) or in-theater (process #9), benefits the most from the adoption and use of

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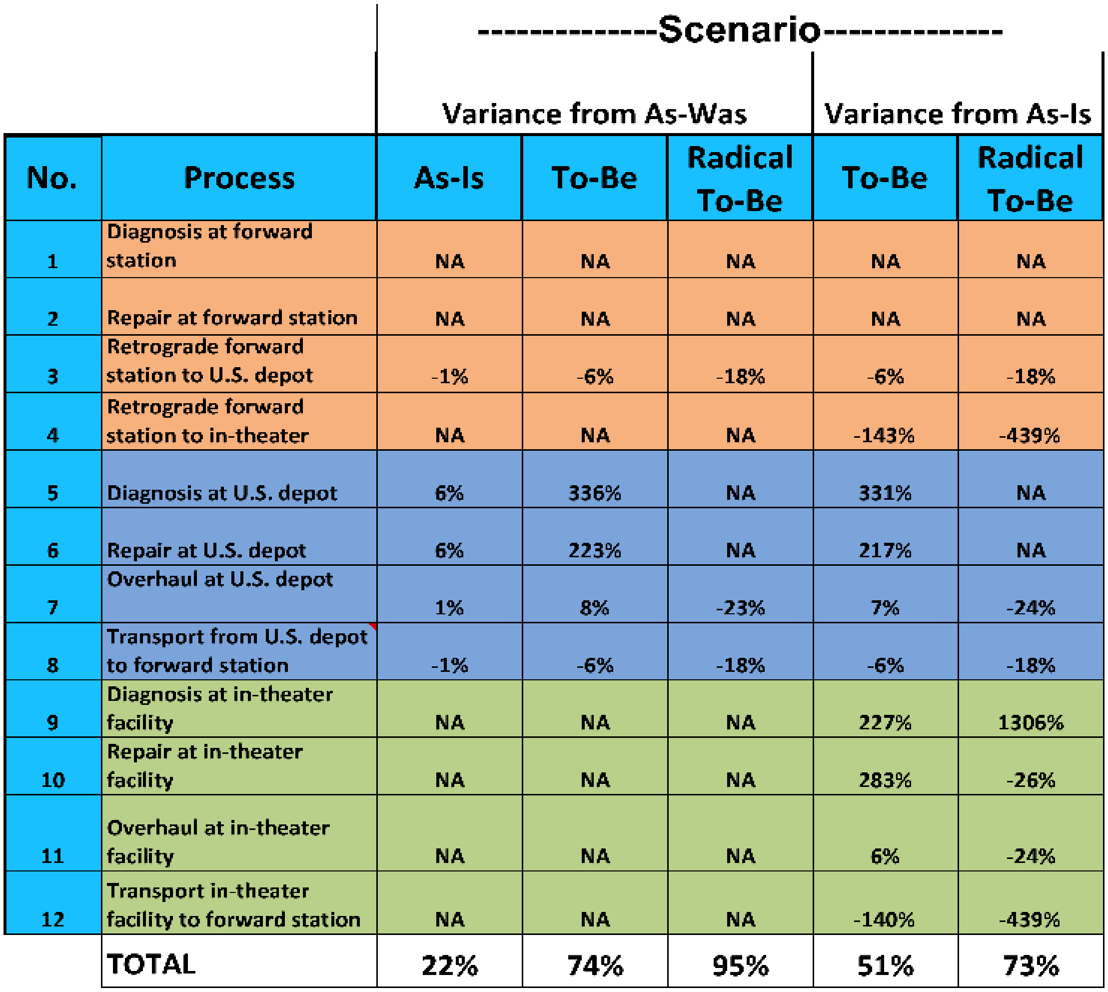
[3] NA – Not Applicable because the process is not used in the scenario

the three advanced technologies. The ROI for diagnosis increases from 90% in the As-Was scenario and 95% in the current As-Is scenario to over 1400% when performed in-theater in the Radical To-Be scenario.

Table 8 shows the ROK and ROI improvement of the As-Is, To-Be, and Radical To-Be scenarios over the As-Was scenario and the ROK and ROI improvements of the To-Be and Radical To-Be scenarios over the As-Is scenario.

Table 8. Differences in Returns on Investment (ROI) of Simulated Scenarios of Repair of Army's Up Armor HMMWV Fleet[4]



		--------------Scenario--------------				
		Variance from As-Was			Variance from As-Is	
No.	Process	As-Is	To-Be	Radical To-Be	To-Be	Radical To-Be
1	Diagnosis at forward station	NA	NA	NA	NA	NA
2	Repair at forward station	NA	NA	NA	NA	NA
3	Retrograde forward station to U.S. depot	-1%	-6%	-18%	-6%	-18%
4	Retrograde forward station to in-theater	NA	NA	NA	-143%	-439%
5	Diagnosis at U.S. depot	6%	336%	NA	331%	NA
6	Repair at U.S. depot	6%	223%	NA	217%	NA
7	Overhaul at U.S. depot	1%	8%	-23%	7%	-24%
8	Transport from U.S. depot to forward station	-1%	-6%	-18%	-6%	-18%
9	Diagnosis at in-theater facility	NA	NA	NA	227%	1306%
10	Repair at in-theater facility	NA	NA	NA	283%	-26%
11	Overhaul at in-theater facility	NA	NA	NA	6%	-24%
12	Transport in-theater facility to forward station	NA	NA	NA	-140%	-439%
	TOTAL	22%	74%	95%	51%	73%

NA – Not Applicable because the process is not used in the scenario

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[4] NA – Not Applicable because the process is not used in the scenario

The positive variances in the bottom row of Table 8 indicate that the advanced technologies significantly improve equipment repair. More specifically, ROI increases 95% from the traditional processes (As-Was) to the envisioned scenario (Radical To-Be) and 73% from the current processes (As-Is) to the envisioned scenario (Radical To-Be). Table 8 also shows losses for shipping equipment back to U.S. depots and back (processes #3, #4, and #12) as the three advanced technologies are increasingly adopted and used (moving right across the rows). This shows that the in-theater and forward station repairs allowed and facilitated by the three advanced technologies make returning equipment to the United States for repairs less attractive with advanced technologies.

Estimating Cost Savings in Shrinking the Mountain

Costs for the scenarios can be estimated using the definition of Return on Investment (ROI):

$$ROI = (Benefits - Costs) / Costs$$

which can alternatively be written as Cost = Benefits / (ROI + 1)

The equation above was used with the benefits and Returns on Investment (Table 7) to estimate the costs of each scenario in millions of dollars. Benefits were estimated as the value of the up armor HMMWV fleet, specifically as 23,800 vehicles * $169,428/vehicle[5] = $4,032,386,400. Results are shown in Table 9.

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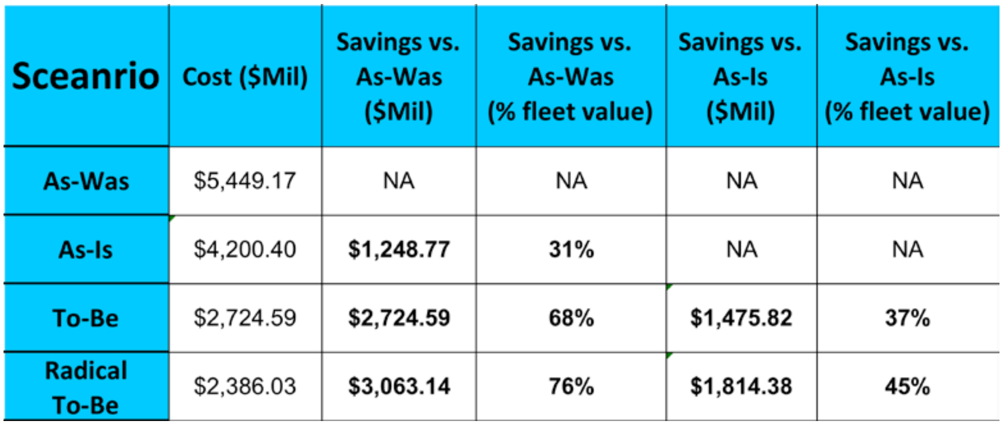
[5] Cost estimates of a single up armored HMMWV range from $169,248 (DoS, xxxx) to $220,000 (Keyes, 2011).

Table 9. Estimated Costs and Savings in Army's Up Armor HMMWV Fleet of Four Scenarios



Sceanrio	Cost ($Mil)	Savings vs. As-Was ($Mil)	Savings vs. As-Was (% fleet value)	Savings vs. As-Is ($Mil)	Savings vs. As-Is (% fleet value)
As-Was	$5,449.17	NA	NA	NA	NA
As-Is	$4,200.40	**$1,248.77**	**31%**	NA	NA
To-Be	$2,724.59	**$2,724.59**	**68%**	**$1,475.82**	**37%**
Radical To-Be	$2,386.03	**$3,063.14**	**76%**	**$1,814.38**	**45%**

The savings shown in Table 9 are consistent with or conservative when compared to the results reported by industry adopters of these technologies described previously in this report (e.g., >30% cost savings for 3DST alone and up to 80% for AM). The results suggest that the adoption of the current processes have saved almost $1.2 billion in the up armor HMMWV fleet over the traditional approach and that the additional adoption and use of the advanced technologies can save an additional $1.8 billion or more.

Potential savings of full implementation of an advanced technology strategy (Radical To-Be scenario) for multiple fleets can be estimated using the 45% of fleet value savings in Table 9. Accurate and consistent estimates of the value of U.S. Army equipment are difficult to obtain. However, order of magnitude savings can be estimated using available values. Banian (2013) estimated the value of U.S. Army equipment in Afghanistan to be $28.454 billion. In 2008 the GAO (2008) estimated that the $15.5 billion of DoD materiel and equipment in Operation Iraqi Freedom is theater provided equipment that represents 80% of the total used in Iraq. These estimates suggest a materiel and equipment value of at least $47 billion (28.254+(15.5/.80)=47.7b) for the two operations. Potential savings for future operations of similar scale using the Radical To-Be savings estimate are $21.46 billion (=$47.7b * 45%). This estimate is based on a single fleet of vehicles. Savings could be larger because multiple fleets of equipment could share repair resources, such as hardware, software, and people, thereby reducing costs further.

Conclusions

Three advanced technologies were examined for their capability to reduce the cost of shrinking the mountain of equipment generated by military operations. Three dimensional scanning technology, additive manufacturing, and product lifecycle management have evolved far enough to have demonstrated their potential benefits to diagnosis, repair, and overhaul processes. Forecasted evolutions of the technologies based on the literature were used to develop four realistic scenarios of their application to military equipment repair in the past, present, near future, and distant future. These four scenarios were then modeled using the Knowledge Value Added methodology to estimate returns on knowledge and returns on investment using the up armored HMMWV fleet as an example. The results indicate that the advanced technologies benefit repair operations and generate significant savings, especially by performing damage diagnosis in-theater and at forward stations. The results were used to estimate potential savings of more than $1.8 billion for the up armor HMMWV fleet and at least $21 billion for operations similar to the scale of those in Iraq and Afghanistan.

We conclude that to capture the very large potential savings the DoD should accelerate its adoption of 3DST, AM, and PLM for equipment repair. That acceleration should include testing the use of these technologies for a broader spectrum of applications (e.g., parts types, processes), the expansion of their use in applications that have been demonstrated to provide benefits, and the revision of processes to exploit these technologies (especially reduce shipping to and from distant depots). Doing so will have important impacts on both practice and research. More military operations support will be located closer and at forward stations. Damage diagnosis and repair will occur much faster, more accurately, and be targeted. Demands on repair operations will be forecasted in real time based on data from embedded sensors that communicate equipment conditions to support units. Research will be needed to understand and develop effective and efficient processes for these new operations. First steps can include research that learns from existing technology applications and applies that knowledge across multiple equipment types, fleets, and services.

Military repair operations will experience growing pains as the adoption of advanced technology force operational and support changes. But these changes will result in very large cost savings and increased operational flexibility. By exploiting advanced technologies the DoD can accelerate and reduce the cost of shrinking the mountain, increase the value of that materiel, and improve the operational capability of U.S. military forces.

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