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Shrinking the “Mountain of Metal”: The Potential of Three Advanced Technologies

David N. Ford—received his BS and MS from Tulane University and his PhD from the Massachusetts Institute of Technology. He is the Urban Beavers Professor of Construction Engineering and Management in the Zachry Department of Civil Engineering, Texas A&M University. He also serves as a research associate professor of acquisition with the Graduate School of Business and Public Policy at the U.S. Naval Postgraduate School (NPS) in Monterey, CA. Prior to a career in academia, Dr. Ford designed and managed the development of constructed facilities in industry and government. [davidford@tamu.edu]

Thomas J. Housel—specializes in valuing intellectual capital, knowledge management, telecommunications, information technology, value-based business process reengineering, and knowledge value measurement in profit and non-profit organizations. He is a tenured full professor for the Information Sciences (Systems) Department at NPS. He has conducted over 80 knowledge value added (KVA) projects within the non-profit, Department of Defense (DoD) sector for the Army, Navy, and Marines. Dr. Housel also completed over 100 KVA projects in the private sector. The results of these projects provided substantial performance improvement strategies and tactics for core processes throughout DoD organizations and private sector companies. [tjhousel@nps.edu]

Johnathan C. Mun—is a research professor at NPS and teaches executive seminars in quantitative risk analysis, decision sciences, real options, simulation, portfolio optimization, and other related concepts. He received his PhD in finance and economics from Lehigh University. He is considered a leading world expert on risk analysis and real options analysis. Dr. Mun has authored 12 books and is the founder and CEO of Real Options Valuation Inc. [jcmun@realoptionsvaluation.com]

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 much 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.

Introduction

> “To ensure a high-performing and agile supply chain, DoD materiel managers shall leverage modern technologies … to enhance material management processes.”
>
> —*DoD Supply Chain Materiel Management Policy*, Sec. 7a, DoD Instruction No. 4140.01, 2014

Military campaigns such as Operation Iraqi Freedom (OIF), Operations Enduring Freedom (OEF), and the war in Afghanistan required vast amounts of equipment and a substantial supply chain to support operations. For example, over 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 Corp 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 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 DoD challenge. The DoD’s reconstitution process, the process whereby materiel from the Mountain can be certified for reuse making it available again for operational use (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.

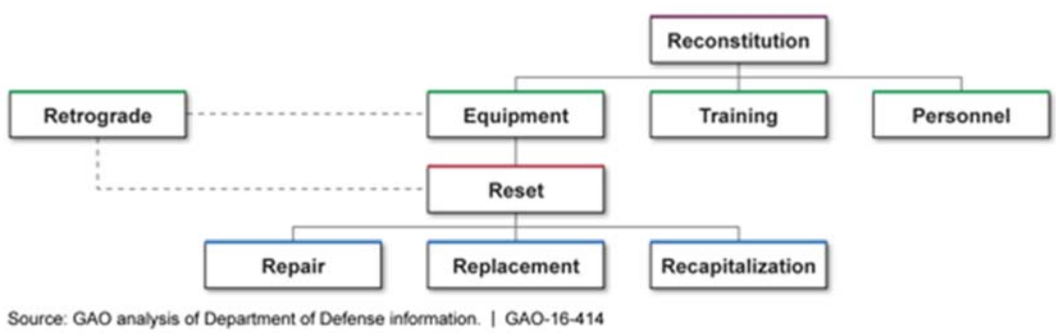

Figure 1. Relationship Between Reconstitution, Retrograde, and Reset Activities (GAO, 2016)

In theater operations, increased use and harsh operating conditions during operations 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). Gen. 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.

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 Corp costs to eliminate the mountain approaches $1 billion (CBO, 2007).

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:

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 DLA 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, saving time, and maximizing availability (FM63-1). 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

[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.

brought their own equipment. This process was used for hundreds of thousands of pieces of equipment deployed to Iraq, Afghanistan, and surrounding areas (CBO, 2007).

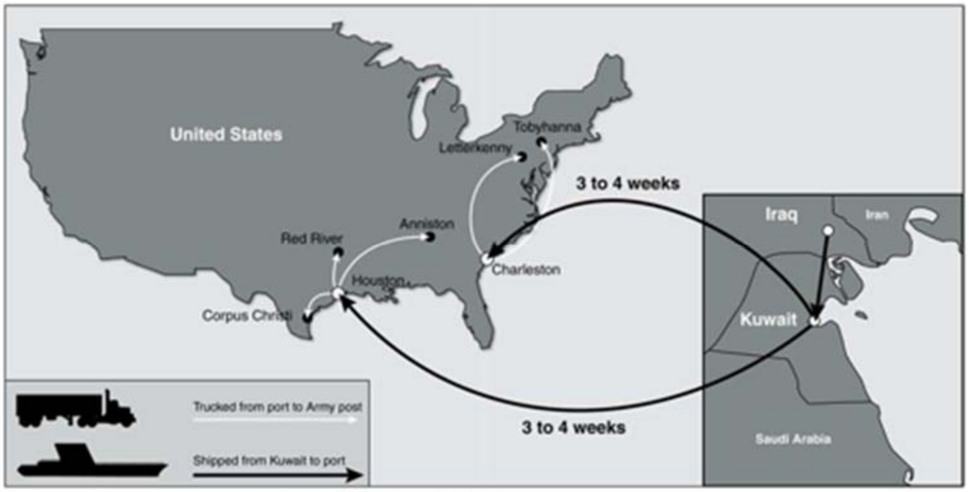

Figure 2. Retrograde of Equipment Leaving Southwest Asia and Returning to the United States for Reset
(GAO, 2012)

The Army uses the reset process to manage damaged equipment. “Reset” is the term for “a series of repair, recapitalization, and replacement actions to restore unit’s equipment to a desired level of combat capability” (Figure 3). This process repairs all damage and performs all routine maintenance (GAO, 2006). 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” (Aquipedia, 2017). The Marine Corps published a reset implementation plan and the Army published information on aspects of the reset process in 2016 (GAO, 2016).

In-Theater Maintenance, Repair, and Overhaul: The Theater Sustainment Stocks (TSS) and the Theater 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 over 400 types of vehicles and other equipment in theater for deployment with arriving units. The Marine Corp has a similar program named Forward In-Stores. In at least 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.

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 (3DST)

Three-dimensional laser scanning technologies 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 measure parts for accurate fit. Other industries using the technology include:

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

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

- ***Architectural & Civil Engineering***. Used to capture as-built documentation of existing buildings and structures such as bridges provides architects and contractors with exact dimensions. Building Information Models (BIM) can be developed to retrofit projects.
- ***Asset & 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).

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

Lu, Li, and Tian (2015) contrast 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 involves a number of steps from a 3D CAD model to a physical 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. The model can be created using 3D laser scanning.
- **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 some 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 enables 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.

AM is already a staple in many manufacturing processes and is being increasingly 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 will be used 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 Company 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.

Product Lifecycle Management (PLM) (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, “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.

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.

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 they 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:

- Tabletop scanning and mapping of fixed objects
- Portable, handheld (no mechanical fix to the scanned object) mapping of freeform surfaces (Allard et al., 2013)
- Translation from point cloud collected by scanning to CAD files for design and manufacturing

Potential future capabilities of 3D scanning technology include:

- 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 upon 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:

- 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:

- 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). For example, 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 transduces (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:

- 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:

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

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; 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 1), use in the near future (5–10 years) (Table 2), and use in the distant future (more than 10 years) (Table 3). Location vs. Technology tables with cells describe activities (e.g., maintenance, minor repair, overhaul, and diagnosis

Table 1. Current Repair Applications of Three Advanced Technologies

Location	Current Applications	3D Scanning Technology (3DST)	Additive Manufacturing (AM)	Product Lifecycle Management (PLM)
		Innovative Technology		
Location	US depot	-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
Location	In-Theater	-None or experimental	-Limited use with basic materials	-Limited use
	Forward station	-None	-None	-None

Table 2. Near-Future Repair Applications of Three Technologies

Location	Near-Future Applications	3D Scanning Technology (3DST)	Additive Manufacturing (AM)	Product Lifecycle Management (PLM)
		Innovative Technology		
Location	US depot	-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
Location	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 3. Distant-Future Repair Applications of Three Technologies

	Distant-Future Applications	Innovative Technology		
		3D Scanning Technology (3DST)	Additive Manufacturing (AM)	Product Lifecycle Management (PLM)
Location	US depot	-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
Location	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
Location	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 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 et al., 2016)

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 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. 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.

For the purpose of this study KVA was used to measure the value added by the human capital assets and the system assets 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. KVA quantifies value in two key productivity metrics: return on knowledge (ROK) and return on investment (ROI).

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.

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 3, 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.

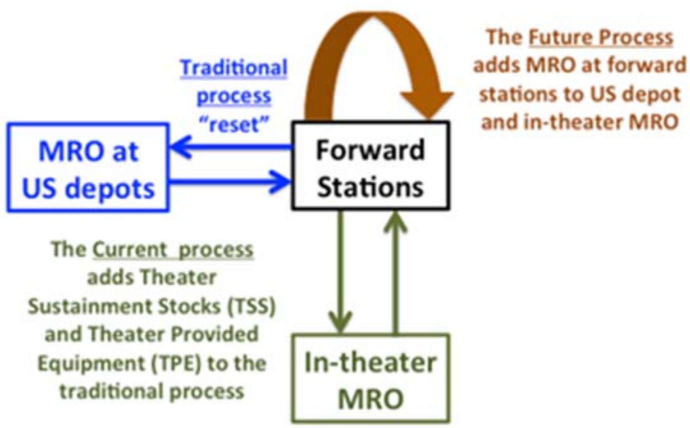

Figure 3. Processes for Shrinking the Mountain

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.
- **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.

- **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 chosen 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 what 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 and 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.

Results

Returns on Knowledge and Returns on Investment

Table 4 shows the simulated returns on knowledge (ROK) and returns on investment (ROI) of the four scenarios described above.

Table 4. Returns of Simulated Scenarios of Repair of Army's HMMWV Fleet

		--------------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 US 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 US depot	190%	90%	195%	95%	526%	426%	NA	NA
6	Repair at US depot	211%	111%	217%	117%	433%	333%	NA	NA
7	Overhaul at US depot	51%	-49%	52%	-48%	59%	-41%	28%	-72%
8	Transport from US 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%**

Note. NA=*Not applicable* because the process is not used in the scenario.

Table 4 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 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 5 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 5. Differences in Returns on Investment (ROI) of Simulated Scenarios of Repair of Army's Up Armor HMMWV Fleet

		--------------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 US depot	-1%	-6%	-18%	-6%	-18%
4	Retrograde forward station to in-theater	NA	NA	NA	-143%	-439%
5	Diagnosis at US depot	6%	336%	NA	331%	NA
6	Repair at US depot	6%	223%	NA	217%	NA
7	Overhaul at US depot	1%	8%	-23%	7%	-24%
8	Transport from US depot to forward	-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%

Note. NA=*Not applicable* because the process is not used in the scenario.

The positive variances in the bottom row of Table 5 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 5 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

The definition of Return on Investment (ROI), the benefits, and Returns on Investment (Table 4) were used to estimate the costs of each scenario in millions of dollars.[3] Benefits were estimated as the value of the up armor HMMWV fleet, specifically as 23,800 vehicles * $169,428/vehicle[4]= $4,032,386,400. Results are shown in Table 6.

Table 6. 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 6 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 6. 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, and Cruz (2013) estimated the value of equipment in Afghanistan at the beginning of 2013 as $28 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 $21.46b (=$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.

[3] ROI = *(Benefits–Costs)/Costs, which can alternatively be written as Cost=Benefits/(ROI + 1).*
[4] Cost estimates of a single up armored HMMWV range from $169,248 (DoD, 2014) to $220,000 (Keyes, 2011).

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 armored 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 their use 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, be more accurate, 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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Acquisition Research Program
Graduate School of Business & Public Policy
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net