Final Report

Department of Defense Additive Manufacturing Roadmap

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1 EXECUTIVE SUMMARY

AM offers considerable opportunity to create DoD supply chain efficiencies and enhance warfighter capabilities. In Spring 2016, America Makes and Deloitte facilitated the development of Additive Manufacturing (AM) technology roadmaps for the Department of Defense. The US Army, Department of the Navy (DON), US Air Force (USAF), and Defense Logistics Agency (DLA) jointly contracted with the National Center for Defense Manufacturing and Machining (NCDMM) through the America Makes cooperative agreement to create a set of technology roadmaps for Additive Manufacturing (AM). America Makes and Deloitte conducted a total of nine roadmapping workshops, facilitating two workshops with each Service/Agency and one joint workshop that brought stakeholders from all four organizations together.

The results of these workshops were one individual AM technology roadmap for each organization (total of four), and one integrated, joint roadmap, representing the combined interests of all stakeholders. The individual roadmaps focused on current state, future state, and the identification of the technology gaps existing between the two states. The joint roadmap focuses on identifying areas of commonality between the individual roadmaps.

The workshops aligned to the technical focus areas from the America Makes Technology Roadmap. Each technical focus area is defined below:

Design – Drives technological advancements in new design methods and tools.
Material – Builds the body of knowledge for benchmark AM property characterization data and eliminating variability in "as-built" material properties.
Process – Drives technological advancements that enable faster, more accurate, and higher detail resolution AM machines.
Value Chain – Encourages technological advancements that enable step change improvements in end-to-end value chain cost and time to market for AM produced products.

Although technology development and transition requirement identification was the primary focus of the DoD Roadmapping workshops, enabling technology is critical to ensuring a robust AM ecosystem. Over the course of the workshop process, participants from Army, DLA, DON, and USAF identified three key enablers (non-technology factors/needs crucial to the eventual success of DoD AM efforts).

Cultural Change – Increasing knowledge of and comfort with AM, driving institutional acceptance.
Workforce Development – Readying the DoD workforce (acquisition, R&D, manufacturing, etc.) with the skills to harness AM.
Data Management – Developing the policies, architectures, and procedures to properly manage massive, multimodal AM data.

This integrated DoD Additive Manufacturing (AM) Roadmap provides a foundation and framework for focusing any desired collaboration and coordination of the DoD's activities in AM to systematically and efficiently mature the technology for multiple DoD applications. Individuals and organizations may utilize this strategic document to identify areas of focus and address roadmap objectives and technology elements together, where appropriate and beneficial.

2 INTRODUCTION

Additive manufacturing (AM), which includes the commonly used term "3D printing," is a rapidly growing and changing discipline. While the technology and associated processes have been used for several decades, AM is rapidly advancing in capability and expanding in applications, increasing the potential impact of this technology. Significant investments are being made, in both the private and public sector, in developing AM technologies for applications ranging from prototypes to mass-produced end-items, from tooling to custom medical implants. Each of the Department of Defense (DoD) components and agencies are investing in AM technologies, desiring to utilize and mature AM in order to affect the entire DoD 5000.02 defined acquisition lifecycle: from enabling new products to reducing logistics and sustainment costs. The commercial and defense industries are also investing in maturing AM for multiple applications and there is a significant international investment in the technology. According to the 2016 Wohler's Report, the worldwide AM market in 2015 was $5.17B. However, much of this investment is being directed at proprietary and specific applications, resulting in duplication of efforts, customized data sets and ultimately slower adoption of the technology across the industry. It is therefore imperative that DoD investment in AM be broadly coordinated throughout its organizations and informed by broader government and industry initiatives in order to ensure rapid adoption.

America Makes, The National Additive Manufacturing Innovation Institute, was established in August 2012 as the first of up to 45 presidentially-established public-private partnerships under the National Network of Manufacturing Innovation (NNMI) (recently re-branded as Manufacturing USA). America Makes seeks to accelerate technology development and adoption associated with AM by addressing manufacturing technology challenges common to the AM community. To logically coordinate AM investments and efforts, America Makes has, with the input of its membership, developed a technology roadmap accounting for major swim lanes of activities and associated technology development efforts related to the maturation of AM. This roadmap has already paid dividends for the industrial partners within America Makes – for example, companies such as Raytheon and Rolls Royce have restructured their internal R&D investments to align with the roadmap. It has become a rallying point for the broader AM community, effectively communicating the needs and opportunities for AM technology maturation. The greatest value has been the existence of a single, authoritative, AM-community developed product that is open for anyone in the industry to use. However, this roadmap does not fully capture the DoD's input or requirements, as the America Makes roadmap encompasses the broad needs of all industry stakeholders.

As AM continues to be a major topic of interest, the need for a coordinated plan to collectively mature AM in support of DoD requirements is clear. In December 2014, representatives from the Army, Navy, Air Force, Defense Logistics Agency (DLA) and the office of the Deputy Assistant Secretary of Defense for Manufacturing & Industrial Base Policy (DASD(MIBP)) met with senior leaders at America Makes to discuss collaboration on a DoD AM technology roadmap. Each component sought to develop an AM technology roadmap specific to its needs and then integrate those roadmaps into a DoD-level AM technology roadmap.

A DoD AM technology roadmap is necessary for several reasons. In line with its "Third Offset Strategy", the DoD is investing in AM technologies with the goal of establishing this "game changing" technology as a means to improve logistics, enable new and improved products and increase materiel readiness. An integrated DoD roadmap provides a means of coordinating these investments, effectively communicating within and external to the Department the current needs and planned efforts related to AM technology development. This communication is critical to marshalling resources, sharing the DoD's needs for AM technology maturation with the industrial base, and for systematically maturing the technology for DoD applications. It efficiently and effectively identifies common areas of interest across the DoD and facilitates the development of joint strategies and plans to collaboratively address these, avoiding redundancy and duplication of efforts. By bringing together key subject matter experts, stakeholders and end users from across the DoD, the effort focuses on facilitating discussions among DoD component organizations that otherwise may not occur. Finally, the development and delivery of an AM technology roadmap provides starting points for the strategic application of AM throughout the DoD. By projecting technology maturation timelines, deliverables and required resources, DoD program managers, logistics and production organizations, the testing and evaluation community and senior leaders are able to better manage expectations and plan for the implementation of AM.

3 APPROACH / METHODOLOGY

3.1 Background and Purpose

In Spring 2016, America Makes and Deloitte facilitated the development of AM technology roadmaps for the Department of Defense. America Makes was contracted by the US Army, Department of the Navy, US Air Force, and DLA to create a set of technology roadmaps for AM in the DoD community. A total of nine roadmapping workshops were conducted, facilitating two workshops with each Service/Agency and one joint workshop that brought stakeholders from all four organizations together. The results of these workshops were one individual AM technology roadmap for each organization (total of four), and one integrated, joint roadmap, representing the combined interests of all stakeholders. The individual roadmaps focused on current state, future state, and the identification of the technology gaps existing between the two states. The joint roadmap focuses on identifying areas of commonality between the individual roadmaps.

- The multi-phase workshop approach is shown in Figure 3.1.

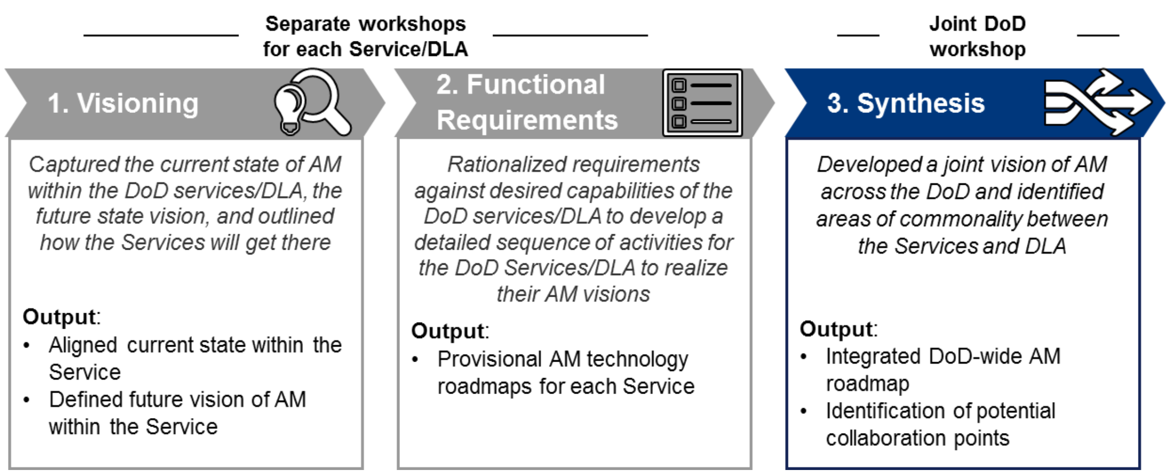

Figure 3.1: Multi-phase Workshop Approach

Each workshop aligned to the AM swimlanes created by America Makes. Brief descriptions of these swimlanes follow below.

Design

The design swimlane is aimed at breaking the paradigm of designing additively manufactured parts like cast or machined parts. Realization of this goal removes the constraints associated with traditional CAD/CAM software and unlocks the potential of AM technology for a variety of applications. The DoD's roadmaps focused on standardization of design tools, lowering barriers to entry for designers and pushing that capability forward (i.e. anyone, anywhere, can intelligently design a part for additive), with particular emphasis on reverse engineering and medical applications.

Material

The material swimlane seeks to advance understanding of materials science behind additive manufacturing. Benchmark data on the material-process-performance relationship and predictive simulations of the complete AM process (i.e. multiscale, multi-physics simulation and Integrated Computational Materials Engineering (ICME)) are an essential component of this, as are standards. In particular, DoD emphasized standardization and management of data/models in a central repository, qualification/certification with advanced ICME, and development of specific types of materials.

Process

The process swimlane is aimed at enhancing the speed, maximizing size, accuracy and resolution of the build process, and improving the surface finish of final parts. The DoD roadmaps highlighted the need for advancement in in-situ sensing and feedback control, the need to develop a suite of new process capabilities (including expeditionary), and a desire for more robust standards.

Value Chain

The value chain swimlane strives to enhance understanding of the complete AM value chain, including business case analysis, complete life cycle analysis, and inspection. Furthermore, this focus area includes digital thread – the IT-based backbone that digitally links various components of the value chain (design, modelling, build process, inspection, performance, etc.) together. The DoD's roadmaps focused on digital thread, building the business/warfighting case for AM, and tightly integrating AM with the traditional supply network.

3.2 Visioning Workshop Approach

The major objectives of the visioning workshop were to:

- Understand the goals of DoD AM Roadmapping.
- Validate the current state of AM in the Service.
- Develop a future state vision for AM for the Service.
- Create a framework to reach the future state vision.

3.3 Functional Requirements Workshop Approach

The goal of these workshops was to have the content necessary to develop a provisional AM technology roadmap for each DoD service and DLA.

The major objectives of the functional analysis workshops were to:

- Validate the outputs from the Visioning Workshop.
- Create the requirements needed to develop the technology elements.
- Prioritize and sequence the Service's AM development plan.
- Analyze the impact of each goal on the Service's mission.

3.4 Joint Synthesis Workshop Approach

The goal of the joint synthesis workshop was to develop a joint DoD-level roadmap which integrated the previously developed technology roadmap for each DoD Service and DLA, and used a common structure and terminology.

The Joint Synthesis Workshop conducted the following series of activities with additional details included in Sections 3.4.1-3.4.5:

- Service / Agency Vision
- Individual Service Presentations
- DoD-wide Roadmap Integration
- Mind Mapping
- Joint Synthesis Workshop Outputs

3.4.1 Service / Agency Vision

At the beginning of the joint workshop, Service/Agency leads presented their vision for AM within their organization, priorities, and vision for the output of the project. Those remarks were captured in Figure 3.2, which also began to document commonalities across the organizations.

A lead from each DoD service and DLA answered the following high-level questions:

- What is the vision for AM in your Service/Agency?
- How do you hope to work with the other Services/Agency?
- What do you hope to accomplish from the roadmapping process?

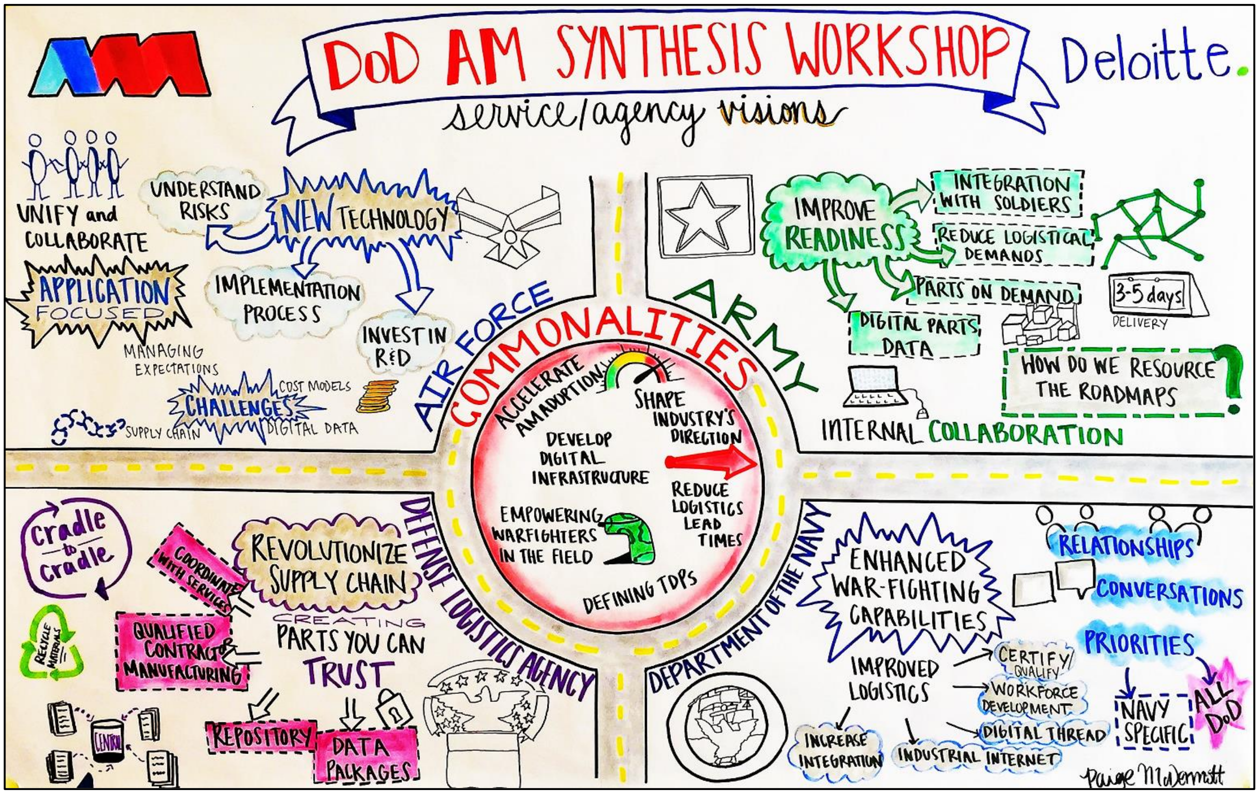

Figure 3.2: Service / Agency Visioning Exercise

3.4.2 Roadmap Integration

The Joint Synthesis Workshop challenged participants to build an integrated DoD roadmap by combining the goals and technology elements, where appropriate, from the individual organizational roadmaps. The integrated goals and technology elements indicate areas where stakeholders identified commonalities and perhaps could collaborate or coordinate.

To level-set the workshop participants, each lead presented their provisional roadmap to the workshop participants. Each of the leads reviewed the outputs from the previous workshop ensuring each participant had a common understanding of each Service/Agency provisional roadmap (objectives and tech elements) for each of the swimlanes. The review included the following:

- Review objectives at a high level for each swimlane
- Explain relevant technology elements
- Explain any areas where the Service/Agency believes they can benefit from coordination

The next step in the process was to complete the Roadmap Integration exercise as illustrated in Figure 3.3. The objective of the exercise was to create a set of integrated objectives (and matching technology elements) across each swimlane. The participants were divided into small swimlane groups to accomplish this task. The participants worked with their swimlane groups to identify overlapping objectives/impacts and map appropriate technology elements to each of those objectives, creating a draft DoD joint roadmap.

The exercise was executed using the following workflow:

Swimlane: Groups were split by swimlane and brought together ideas from all Services/Agency

Goal: Participants developed integrated objectives by grouping and transferring objectives from Service-level roadmaps

Impact: Participants developed integrated impact statements that refer back to Service-level roadmaps

Service/Agency Alignment: Services/Agency indicated alignment with integrated objectives

Technology Elements: Participants transferred relevant technology elements from Service-level roadmaps that aligned to the newly integrated objectives

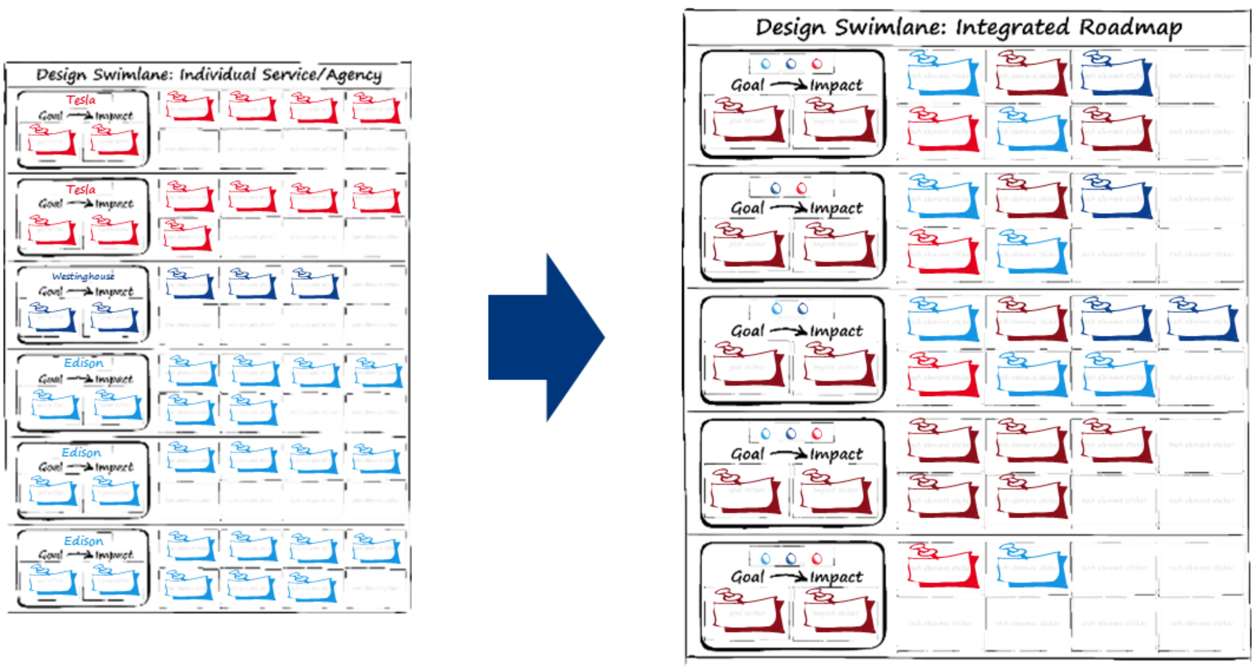

Figure 3.3: Roadmap Integration Exercise

The outputs of the exercise were integrated swimlane-level roadmaps and all Service/Agency objectives were merged or moved over to the integrated roadmap. The tech elements were also correctly mapped to the appropriate objectives and merged where appropriate.

3.4.3 Mind Mapping Exercise

The second stage of the workshop focused on identifying the remaining gaps/commonalities and identifying potential areas of collaboration or coordination. In the mind mapping portion of the workshop, participants worked within their swimlane groups to develop mind maps and structure their ideas on gaps, technology commonalities, and enabler commonalities based on the integrated roadmap. Figure 3.4 highlights an example of a mind mapping exercise.

- Gaps: These are areas on one Service/Agency's provisional roadmaps that another Service/Agency would like to consider for its own organization. Additionally, we would like you to consider any areas that may not be mapped to any Service/Agency but may still need to occur on a DoD level.

- Technology Commonality areas: These are areas where multiple Services/Agencies have overlapping roadmap objectives and can potentially coordinate on R&D of technologies or program development.
- Enabler commonality areas: Identify cross-cutting enablers. While they don't directly correspond to technology elements, they are important focus areas to enable eventual success with each Service/Agency's technology objectives.

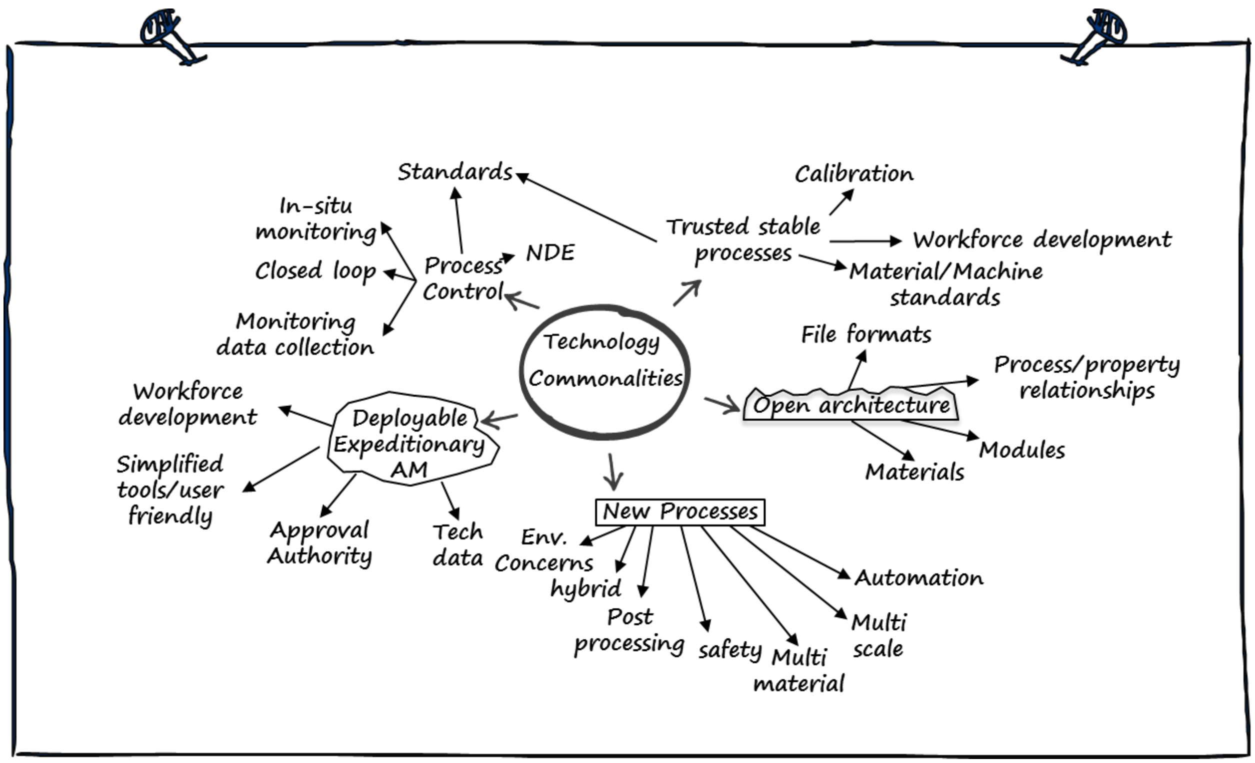

Figure 3.4: Mind Map Exercise (example only)

3.4.4 Joint Synthesis Workshop Outputs

America Makes and Deloitte compiled the workshop outputs into a final integrated roadmap, bringing all integrated objectives and technology elements together into one DoD-wide package. The two main outputs from the Joint Synthesis Workshop were a Joint DoD Technology Roadmap for Additive Manufacturing and a narrative companion guide. Those two documents are included within this report in Sections 6 and 7 and shown in Figure 3.5.

Section 6 - The Joint DoD Technology Roadmap for Additive Manufacturing includes 21 integrated objectives across four America Makes swimlanes (design, material, process, and value chain) and impact statements.

Section 7 – The narrative companion guide accompanies the joint synthesis roadmap, to provide further clarity and detail where appropriate for objectives that participants across all Services/DLA integrated during the Joint Synthesis Workshop.

3.4.5 Joint Synthesis Workshop Participants

Joint Synthesis Workshop Participants are identified in Figure 3.5.

Service/ Organization	Participant	Swimlane Assignment
Air Force	Joe Carignan – Tinker AFB	Design
	Mary Kinsella* – AFRL	Material
	Kristian Olivero – Tinker AFB	Process
	Jamie Gilbert – Tinker AFB	Value Chain
	Mark Benedict – AFRL	AM Genome
Army	Rick Foley – Tobyhanna Army Depot	Design
	CAPT Jeremey Pinson – CASCOM	Material
	Andy Davis* – ManTech	Process
	Vince Matrisciano – PEO Ammunition	Value Chain
	Robert Carter – ARL	AM Genome
DLA	Edilia Correa – Chief, Tech & Qual	Design
	Phillip Radliff – Value Engineering	Material
	Kelly Morris* – Chief, Logistics R&D	Process
	Michael Ball – Chief, Technology Office	Value Chain
	Kyle Hedrick – Exec Sponsor for AM	AM Genome
Department of the Navy	James Pluta – OPNAV N41	Design
	Jenn Wolk – Program Officer, ONR	Material
	Ben Bouffard* – AM Lead, DASN RDT&E	Process
	William (Bill) Frazier – Chief Scientist, NAVAIR	Value Chain
	LtCol Howie Marotto – HQ, Installations & Logistics	AM Genome
America Makes	Ed Morris	Floating facilitator
	Rob Gorham	Facilitator – AM Genome
	John Wilczynski	Facilitator – Design
	Kevin Creehan	Facilitator – Material
	Jennifer Fielding (AFRL, America Makes PM)	Observer
Deloitte	Mark Cotteleer	Workshop lead
	Mark Vitale	Floating facilitator
	Jim Joyce	Facilitator – Value Chain
	Ian Wing	Facilitator – Process

Figure 3.5: Joint Synthesis Workshop Participants, with asterisk (*) indicating lead Service/DLA interface with America Makes/Deloitte team

4 APPLICATIONS WITHIN DOD FOR ADDITIVE MANUFACTURING

The Department of Defense will rely on the 'Third Offset' strategy to ensure that our fighting forces maintain technological superiority in future conflict; this will result from the convergence of several advanced and emerging technologies (unmanned systems, big data, rapid prototyping, etc.). AM will directly enable the employment of these technologies while also providing crucial new means for future sustainment. The convergence of AM with these concepts is essential for ensuring an offset that will outpace the future threats of our adversaries. The table below shows a categorization of application spaces in which AM may be beneficial to the DoD. Many of these exhibit strong commercial benefit to the U.S. industrial base with strong economic growth potential as well as DoD benefit.

The **Maintenance and Sustainment** application space encompasses locations such as logistics centers, depots, and CONUS operating bases. The driver for adopting AM within the DoD maintenance and sustainment environment is primarily for producing acceptable parts on demand to ensure DoD platforms are functional and mission-ready; obtaining those items that have demand but also have chronic supply issues with traditional manufacturing; and hard-to-source and long production lead-time parts. The **Deployed and Expeditionary** application space encompasses locations such as aircraft carriers, submarines, battlefields, OCONUS operating bases, and other unique environments. The **New Part/System Acquisition** application space refers to the adoption of AM into new acquisition platforms, where the part/system is designed for AM and manufactured using AM. Other applications of AM to this environment are manufacturing aides to support conventional manufacturing, and AM prototypes used for rapid design iteration and form/fit tests.

Maintenance and Sustainment

- **Manufacture of parts** typically produced using conventional manufacturing
- **AM repair** of conventionally manufactured parts
- **Manufacturing aides** for support to conventional manufacturing
- **Prototyping** for rapid innovation and reverse engineering

Deployed and Expeditionary

- **Manufacturing of parts** typically produced using conventional manufacturing
- **AM repair** of conventionally manufactured parts
- **Prototyping** for rapid innovation and reverse engineering

New Part/System Acquisition

- **New parts/systems** designed for AM and manufactured using AM
- **Manufacturing aides** for support to conventional manufacturing
- **Prototyping** for rapid part/system development

4.1 Maintenance and Sustainment

For the Maintenance and Sustainment application space, a significant application of AM is the **manufacture of parts** that were typically produced using conventional manufacturing. The main drivers leading the interest in AM *for replacement parts* is rarely based on cost savings (and may in some cases lead to a cost increase), and are more often based on part availability and capability enhancements. Using the original part geometry, the drivers to shift to an AM process typically stem from attempting to mitigate part obsolescence or long lead time issues by turning to AM as a rapid manufacturing technique. Parts/systems traditionally produced using conventional manufacturing may have issues with long production lead times, part obsolescence and/or diminished manufacturing sources and material shortages (DMSMS). For support to electronic systems, AM may be an especially useful approach for hard-to-source specialty components and low-volume replacement electronic systems.

With redesign of conventional parts to a new geometry enabled by AM, further benefits may include light-weighting, less material waste, production cost reductions, part consolidation and enhanced performance. Parts that have low production volumes are particularly desirable for AM vs. conventional manufacturing due to lower tooling costs. These AM part candidates may or may not be redesigned to take advantage of design freedom with AM. Part redesign may stem from a reverse engineering process or from a conversion of 2D drawing (if available) to 3D technical data. AM replacement may not be feasible, due to the unavailability of 3D data, or even 2D drawings and specifications, as well as unknown original design intent. As legacy parts were not designed for AM, an AM replacement part will not be the same as the original from a material property standpoint and AM may not provide the quality or properties over the lifetime required. Understanding designer intent is critical for replacement parts using AM. These challenges are further complicated by the cost of qualification. Opportunities exist for pursuing an AM part when the original supplier is no longer available and requalification would be a requirement with either a traditional or AM process due to the need to qualify a new supplier.

An AM replacement may cost more than the original part, due to not only the AM process and materials, but also the pre-processing (scan, 3D model, redesign for AM, optimize part build, supply/Quality Assurance incoming material), and post-processing (consolidate, machine, heat-treat, inspect, etc.) needed. In this case, the warfighter's readiness would be considered as the driving factor. Strong business cases, including these aspects, must be developed. While maintenance and sustainment of systems is very important to all Services, this application area is of special procurement interest to the Defense Logistics Agency (DLA).

Another general use for AM within the Maintenance and Sustainment environment is for **AM repair** of conventionally manufactured parts due to wear or other damage. AM repair of conventionally manufactured parts may be used with techniques such as directed energy deposition to refurbish worn parts. Issues include repair material compatibility and the interface/bond/weld with the parent material, and qualification of the repaired part.

Manufacturing aides for support of conventional manufacturing processes performed traditionally within maintenance and sustainment environments are also a viable and near-term application of AM. Cost and lead time savings may be achievable with the incorporation of AM manufacturing aides to support conventional manufacturing activities. These include masking to support painting, grit blasting and other surface treatment processes, tooling for sheet metal forming and composite manufacturing, rapid production of fixtures, mounts, patterns, and jigs, and many others. Pushing the limits of AM tooling for higher pressure and temperature environments, such as for composite autoclave processing is also advantageous as well as for repairing forging/casting tools.

Manufacturing Aides for support of conventional manufacturing processes

- *Masking*
- *Tooling*
- *Fixtures*
- *Mounts*
- *Patterns*
- *Jigs*

Rapid **prototyping** using AM within the Maintenance and Sustainment environment already provides multiple advantages for the DoD. Rapid prototyping applications may be for form/fit checks, rapid development for parts or manufacturing aides, and for mock-ups for training purposes. AM may be more intensively applied within acquisition programs to provide prototypes to accelerate defense system development.

4.2 Deployed and Expeditionary

Drivers to utilize AM technology within a Deployed and Expeditionary environment are for **rapid manufacturing of parts** typically produced using conventional manufacturing. With similar motivations in the Maintenance and Sustainment application space, adoption of AM within Deployed and Expeditionary environments exhibit further unique challenges. Motivations for adoption of AM stem from further increased difficulty with obtaining parts critical to complete a mission. Opportunities for AM in this application space are for shortening the logistics tail and producing mission critical parts at the point of need.

Unique needs for this application space include ease of design for AM and reverse engineering procedures for less experienced users and remote operation for design and engineering support (reach back). Other unique challenges include equipment ruggedization, resiliency, mobility, ease of calibration and maintenance. Post processing is also a challenge. While simpler AM approaches and smaller footprints are preferred for Deployed and Expeditionary operations, post processing requires additional equipment. It is desirable to reduce post processing requirements, though they cannot be eliminated for most structural metal applications. Other needs are for enhanced control and containment of the build environment to protect from environmental factors such as dust and humidity. Unique environmental factors also need to be considered for the materials, such as storage and handling, thermal/humidity/salt, and dust/particulates. Deployed and Expeditionary AM also may benefit from the utilization of recycled or even indigenous material feedstocks.

Finally, adopters of AM in a deployed or expeditionary scenario may be willing to adopt a higher risk situation, where a part may be approved for limited use until a “real” part is available from a certified supplier. Balancing these trade-offs, risks and part life limitations need to be wellunderstood and based on mission criticality and known AM part properties including durability and damage tolerance.

In a similar fashion as the Maintenance and Sustainment application space, traditionally manufactured parts may be **repaired using AM**, though this may be more logistically challenging due to the nature of some AM equipment (larger machines, heavy energy requirements).

Prototyping within the Deployed and Expeditionary environment may be also advantageous. AM equipment employed in an expeditionary setting can provide the tools needed for those closest to potential problems to rapidly develop and iterate prospective solutions. These solutions may immediately support operations, or be digitally supplied to engineering activities for development of more robust components. AM may also be employed as a key element in a rapid reverse engineering process.

4.3 New Part/System Acquisition

For **new part/system acquisition**, the drivers for adoption are the expected benefits of AM over traditionally manufactured parts/systems. Army, Department of the Navy, and Air Force are all very interested in applying AM for enhanced capabilities within new part/system acquisition. Typically, these drivers include an enhanced performance or capability not able to be affordably produced using conventional manufacturing processes, such as enabling complex geometry, mass customization, or rapid manufacturing solving a production lead time issue causing an acquisition schedule slip.

Applications for AM to impact new parts, systems, and designs are very diverse and encompass many aerospace, ground and marine vehicle subsystems and even personal protection, sensing, medical and pharmaceutical applications, power and communication, tailored food and shelter.

AM is often considered for enhanced performance through producing complex geometries unable to be produced by other manufacturing methods. These include, for example, complex geometry structures for light-weighting (fuel savings) and new designs for vehicle structures and propulsion components (such as heat exchangers, fuel components, etc.). Opportunities of interest are high value, low production quantity parts with complex geometries, weight reduction of a system through part consolidation or topology optimization, design customization, reduced development cycle time, rapid design iteration, and enhanced performance benefits. The complexity enabled by AM extends not just to the geometry of the part but also to the chemistry and microstructure within the part, with location-specific properties as a possibility.

Other applications of interest include enabling advantages of additive within parts for extreme environments such as corrosive, nuclear, radar/sonar/signature reduction, high-temperature (ceramics, metals), flame, smoke and toxicity-stringent, and high stress ballistic, and energetic environments.

Multi-material and multifunctional AM is also of interest with the potential to use AM for Intelligence, Surveillance, and Reconnaissance (ISR) applications with integrated electronics printed directly on or within a structure, conformal antennas adapted into loadbearing structure, distributed electronics for flight control feedback and structural health monitoring. Electromagnetic Warfare applications for AM also include communication in contested areas with AM-enabled solutions such as conformal apertures and reconfigurable electronics. Other applications for multifunctional AM include integrated power for applications such as energy harvesting, storage, and management to improve system endurance and range.

AM also has the potential to create customized medical products that increase the effectiveness of medical care for the warfighter. Examples include prosthetics, orthotics, casts, splints, and medical device implants. Some unique needs arise for these applications. For example, medical implants need to exhibit biocompatibility, sterility, and must ensure AM-specific issues are overcome such as entrapped powder. Prosthetics must meet mechanical property requirements, and also be biocompatible and hypoallergenic. AM may impact pharmaceutical products through the creation of unique geometries and/or tailored and customized chemistry which are unable to be produced using conventional techniques, enabling advanced performance such as rapid drug delivery.

AM can also provide functionality such as anti-tamper/anti-counterfeit through the development of micro/nano-structured "fingerprints" or "watermarks" on a part to verify part authenticity. A general concern for AM is to ensure cyber-security and anti-tamper for parts designed and produced using AM, where the designs are safeguarded throughout the production process to ensure tampering has not occurred within the supply chain to the design, build files or machine controls.

New DoD production/acquisition systems may benefit from cost and lead time savings with the incorporation of AM manufacturing aides in support of traditional manufacturing processes in a similar fashion as the Maintenance and Sustainment application space. Examples include tooling, fixtures, jigs, masks, and many others.

New Parts/Systems with Potential for Direct Application of AM (designed for AM and manufactured using AM)

- Aerospace, ground and marine vehicle structures and ancillary parts
- Integrated electronics, antennas, structural health monitoring
- Conformal apertures and reconfigurable electronics
- Power and Energy harvesting/storage
- Personal protection such as ballistics and sensing
- Energetics
- Medical implants and prosthetics
- Pharmaceuticals
- Food
- Shelter

In new acquisition, AM processes may be matured in order to provide advanced prototyping for rapid innovation and system/part design and form/fit testing. Benefits include faster design iterations and system engineering component checks earlier in the acquisition cycle for more rapid platform development.

As with any new technology, insertion risk is present with AM and must be managed in accordance to the application and requirements. Lower risk parts are generally pursued in the near term and in each Services' individual plans. Near term opportunities for new parts produced using AM include components for remotely piloted aircraft, microsatellites, liquid rocket engines, munitions, and limited life platforms which may exhibit lower risk and less stringent safety requirements. As confidence is built for AM, longer term implementation opportunities are for full life, non-critical structural applications, embedded electronics/sensors, and even farther term for fracture-critical components.

5 DOD ROADMAP ENABLERS

While technology and transition requirement identification was the primary focus of the DoD Roadmapping workshops, enabling technology is critical to ensuring a robust Additive Manufacturing (AM) ecosystem. Figure 5.1 illustrates the six capability development needs with talent, governance, mission, and insights highlighted as AM enablers focus areas.

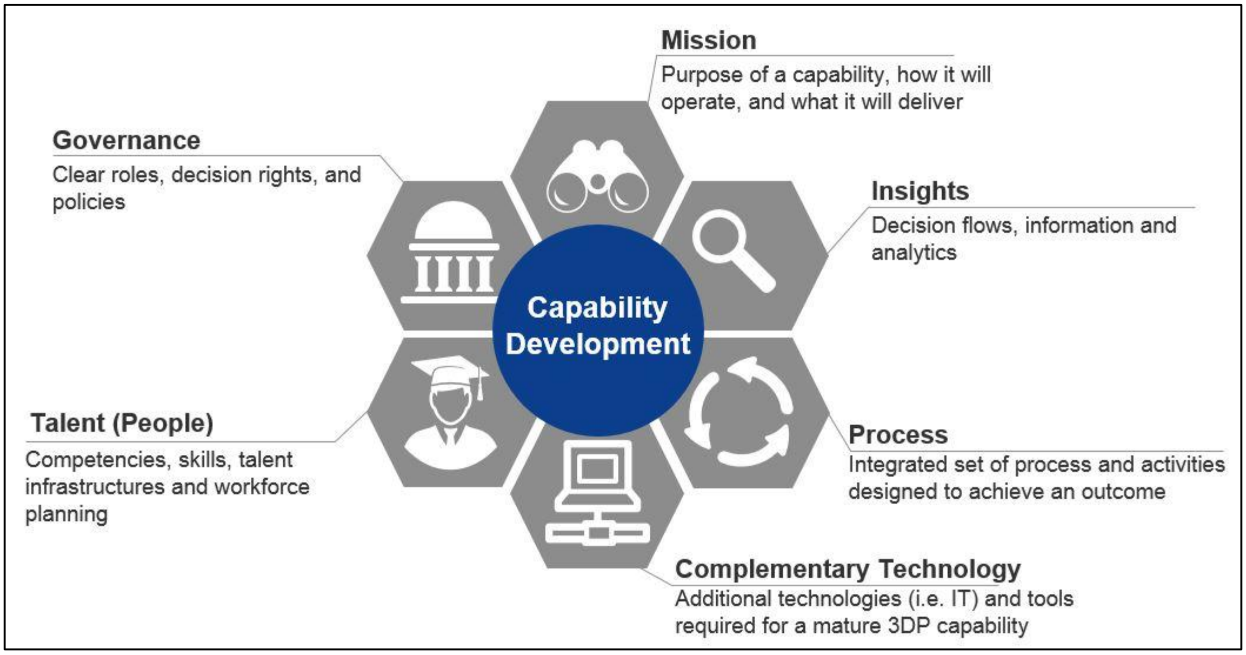

Figure 5.1: Capability Development

5.1 Cross-Cutting Enablers Summary and Takeaways

Each of the four AM roadmap swimlanes executed mind maps to identify cross-cutting commonalities. In summary, these cross-cutting enablers are:

- Cultural Change (Mission) - Enabling cultural change will facilitate increased buy-in for and understanding of AM.
- Workforce Development (Talent) - Appropriately educating staff enables increased AM understanding and production effectiveness.
- Data Management (Insights) - Successful data management facilitates appropriate information exchange and secures sensitive data.

5.1.1 Cultural Change

Definition: Cultural change is the adaptation of the organization to facilitate increased understanding and comfort (at both the individual and collective level) with AM.

<u>Requirements</u>: True cultural change requires strategic alignment, dedicated culture champions, and continuous reinforcement through formal and informal methods.

<u>Impact</u>: Organizations that fully incorporate AM into their culture will have staff that fully understand the AM function and potential within the organization. Staff will then proactively work to actualize that potential in ways that are appropriate to their role.

Key initiatives for cultural change include:

- AM socialization: Socializing AM will ensure that staff across the organization have a deep understanding of AM, the benefits of AM, and how it can be used within the organization. Steps include:
  - Briefing executive-level staff
  - Actively managing expectations at all levels
- AM community: Creating a forum for practitioners interested or involved with AM, alerting the community to new developments and providing resources. Steps include:
  - Setting up a Community of Practice (CoP)
  - Creating and facilitating access to makerspaces
- Collaborative environment: Creating a more collaborative environment can ensure that the right staff connect with the right information and partners. Steps include:
  - Facilitating information exchange
  - Actively encouraging appropriate collaboration

5.1.2 Workforce Development

<u>Definition</u>: Workforce development is a human resources strategy that focuses on increasing skill across the workforce in a given area, in this case AM.

<u>Requirements</u>: Workforce development requires a HR led initiative, development of classes/materials on AM, incentive for staff to participate, and a feedback mechanism for continuous improvement.

<u>Impact</u>: Organizations that succeed in workforce development will have a workforce that is adequately prepared on all levels to interact with AM concepts and production. This enables the harnessing of existing AM capabilities and facilitates the development of new capabilities.

Key initiatives for workforce development include:

- Best practice synthesis: Understanding AM technology developments and applicability in the organizational context. Steps include:
  - Synthesize existing organizational materials
  - Solicit best practices from industry and academia
- Trainings: Create an integrated curriculum of trainings (classroom and hands-on) that are tailored to staff function and level. Steps include:
  - Create standards for trainings/trainers
  - Understand key training content (AM fundamentals, decision tree, etc.)

    - Develop training materials
- Talent recruitment: Attracting and retaining key personnel to strengthen existing capabilities and provide leadership to advance AM capabilities going forward. Steps include:
    - Identify staffing needs
    - Create position requirements and profile candidates
    - Collect candidate feedback to improve experience and retention

5.1.3 Data Management and use of the Digital Thread

Definitions: Data management is the development and execution of architectures, policies, practices, and procedures that properly manage the full data lifecycle needs of an enterprise. *Note: definition from the Data Management Association (DAMA).* Digital thread enables the use of all available information in analyses, uses physics to inform analyses, uses probabilistic methods to quantify risks, and closes the loop from the beginning to the end, and the back to the beginning of the part/system's lifecycle.

Requirements: Data management requires data policy, specs/standards, accessible and secure data repositories, and active database upkeep.

Impact: Organizations with effective data management are able to match the right information with appropriate requestors in a minimal amount of time. This facilitates information exchange and maximizing the effective use of past data on relevant present projects to inform key decisions.

Key initiatives for data management include:

- Database/platform: Develop a platform that comprehensively compiles and stores data in a user-friendly manner. Steps include:
    - Determining requirements for AM data storage
    - Assessing existing databases and determining integration points.
- Data specs and standards: Creating a uniform set of rules for data format, input, use, and storage. Steps include:
    - Assess current formats across enterprise
    - Create rules for data formatting, emphasizing interoperability
    - Create rules for database structuring to correspond with data.
- Cybersecurity: Ensuring that all AM data is secure from design to production to storage.
    - Understand needs to safeguard AM data (end-to-end) from tampering and adversaries.
    - Establish rules for access to database.

6 DOD AM ROADMAP

Figure 6.1 shows the overall graphical representation of the DoD AM roadmap, showing major Integrated Objectives by focus area/swimlane and Impact Statements for each. Figures 6.2 – 6.5 show the graphical representation of the joint DoD AM roadmap with more detail by focus area/swimlane to show the Integrated Objectives and the corresponding detailed, Sequenced Technology Elements. Further descriptions of each Sequenced Technology Element is found in Section 7.

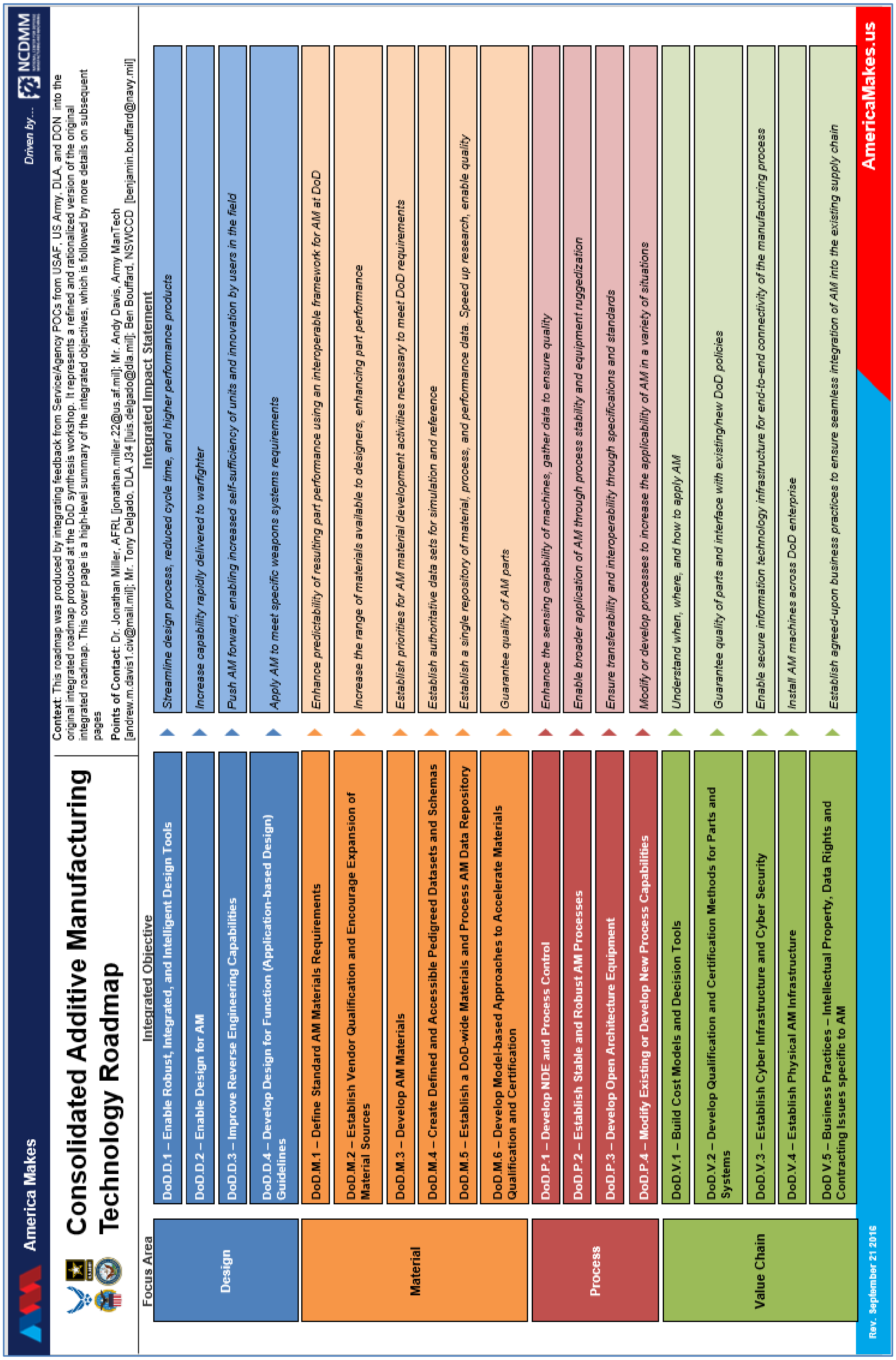

Figure 6.1: Consolidated DoD AM Roadmap

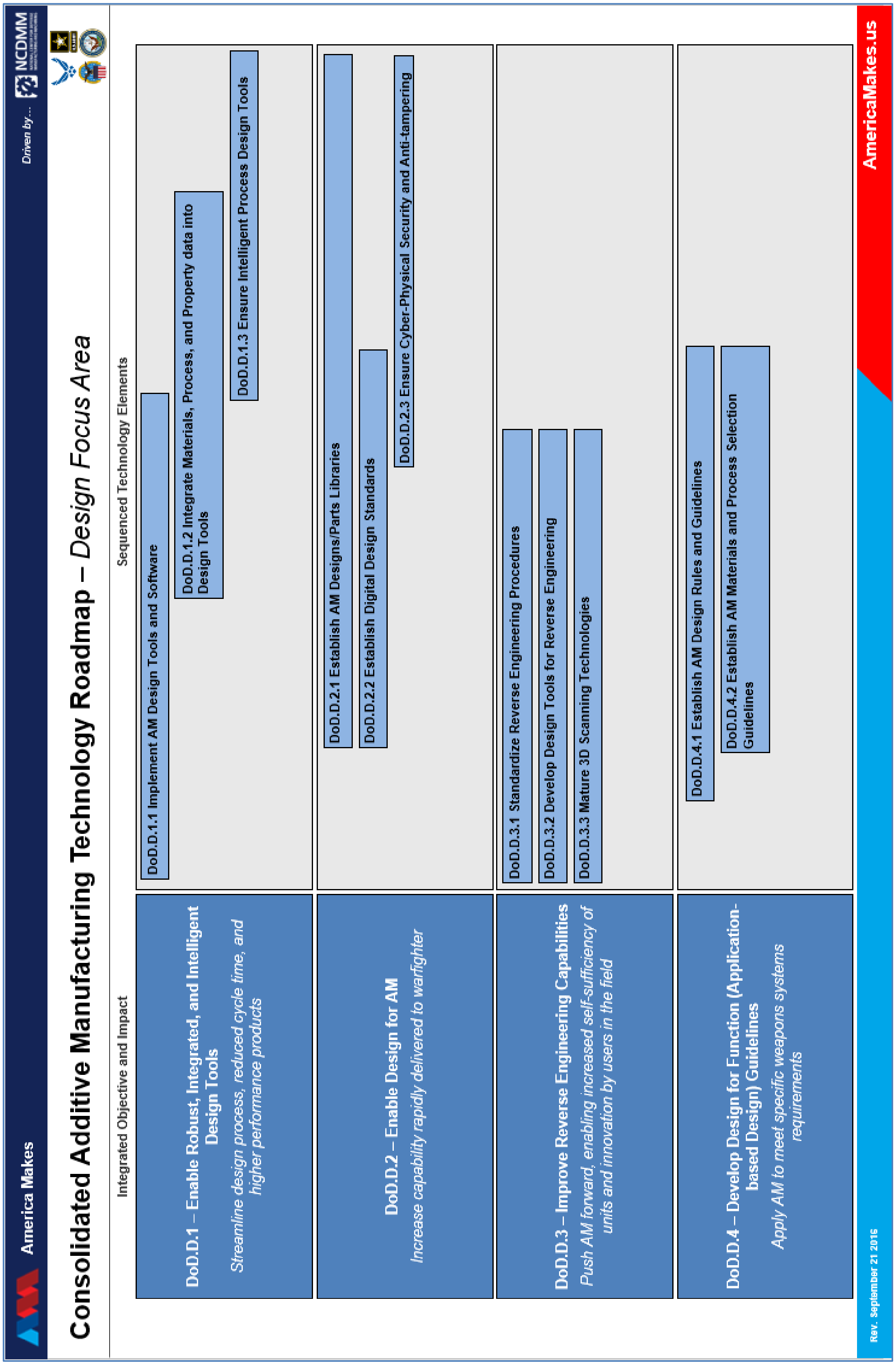

Figure 6.2: Design Focus Area of DoD AM Roadmap

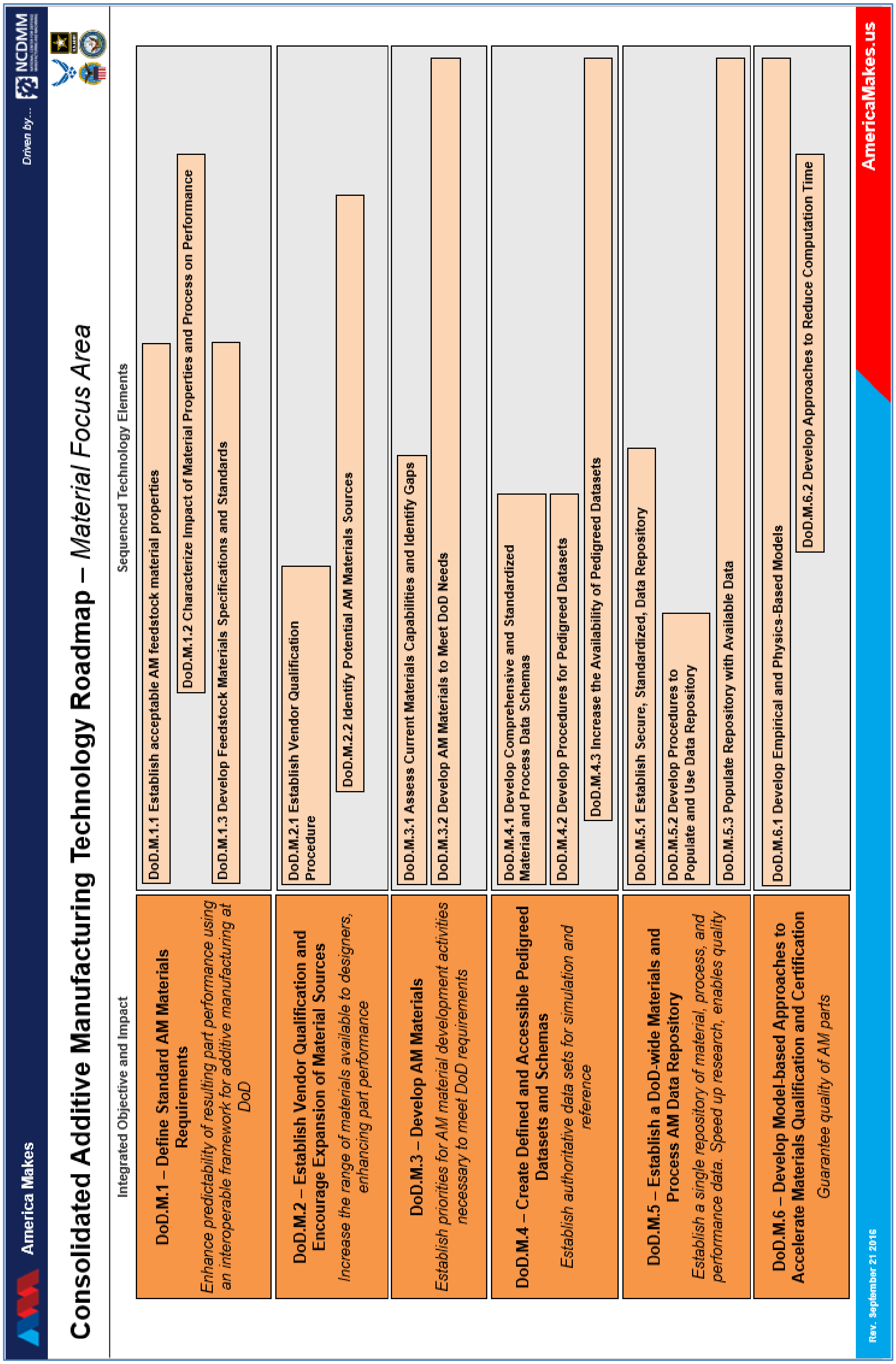

Figure 6.3: Material Focus Area of DoD AM Roadmap

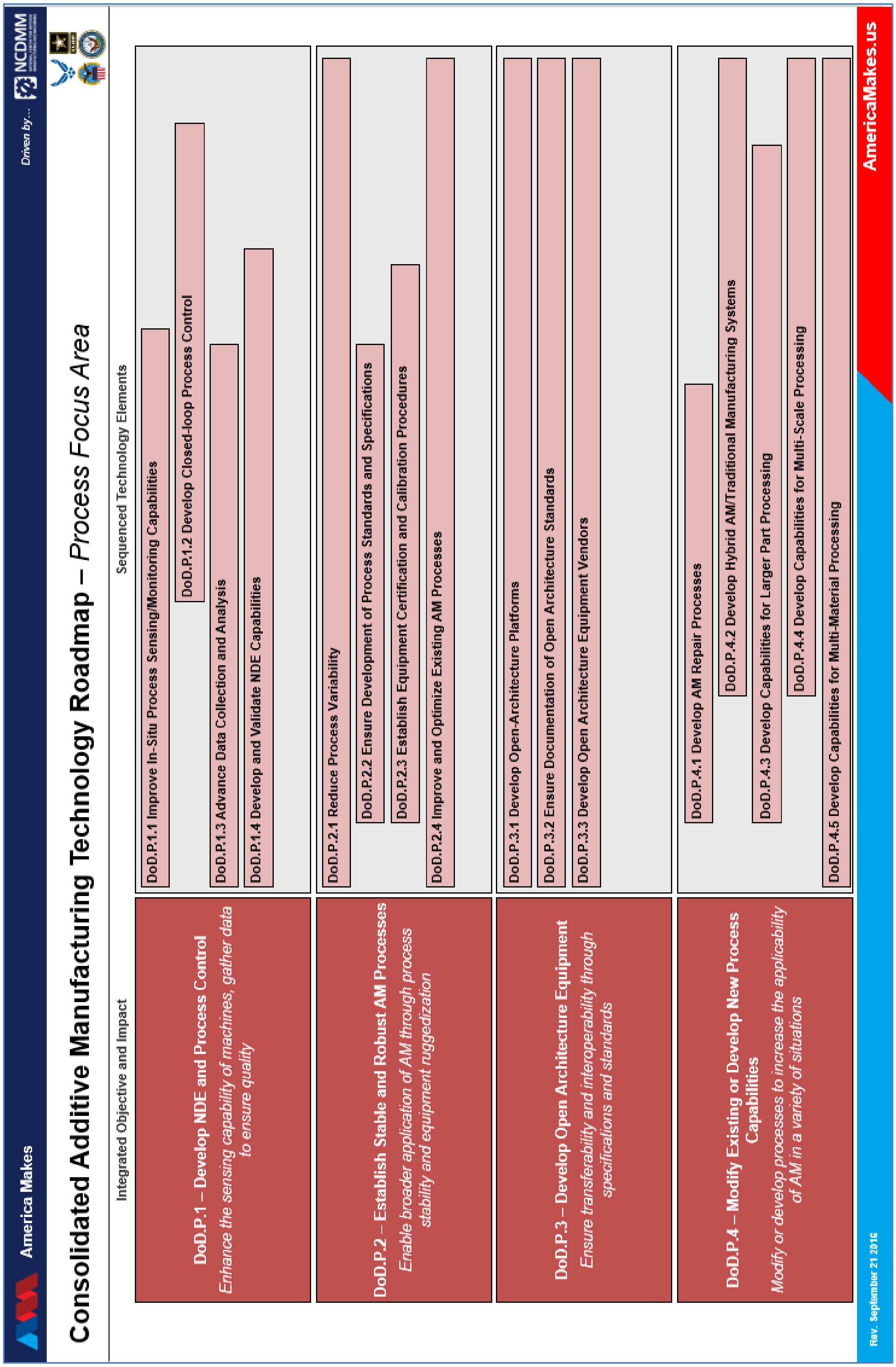

Figure 6.4: Process Focus Area of DoD AM Roadmap

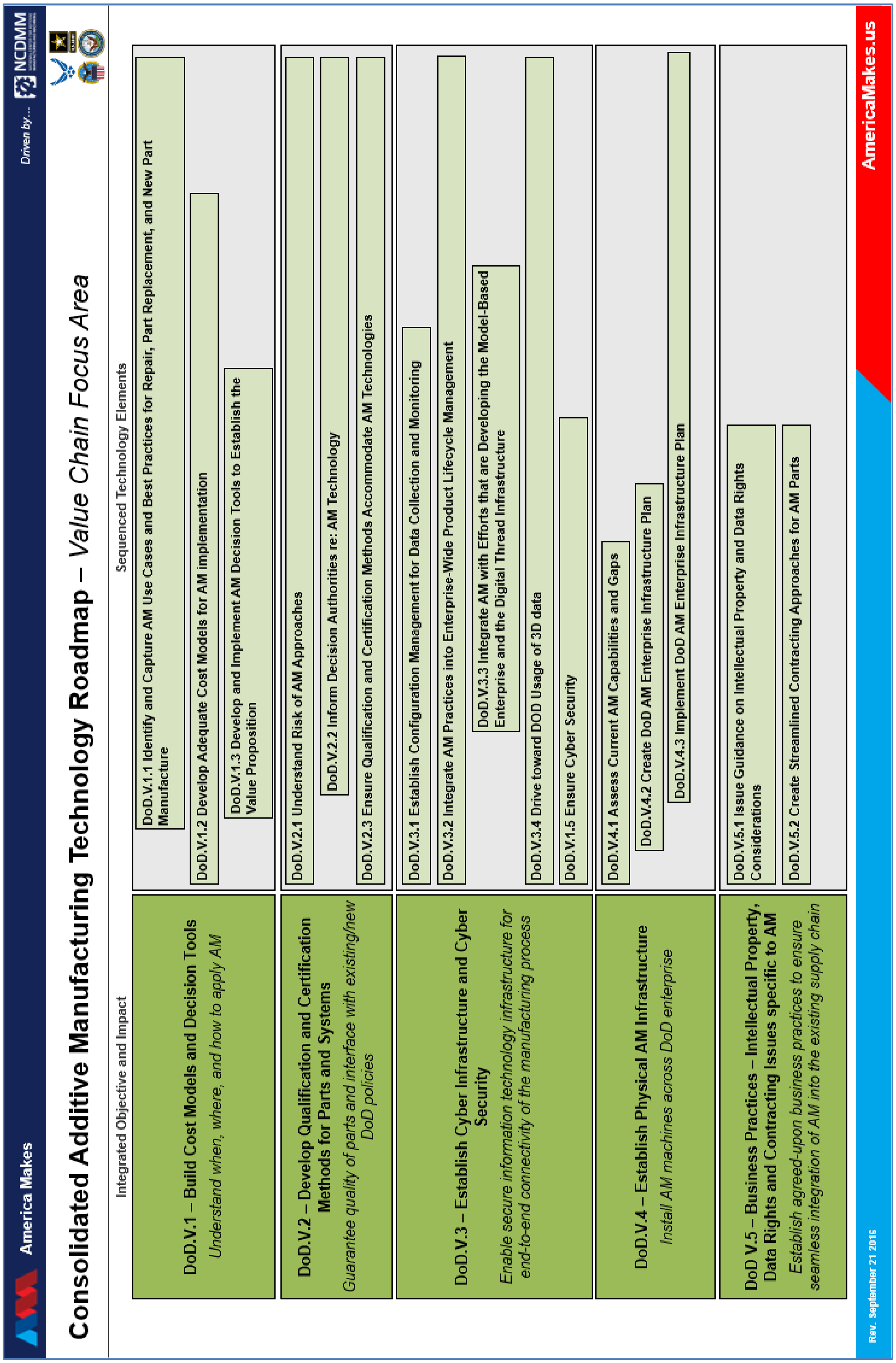

Figure 6.5: Value Chain Focus Area of DoD AM Roadmap

7 DETAILED OBJECTIVES AND TECHNOLOGY ELEMENTS

7.1 Design Objectives and Technology Elements

DoD.D.1. Enable Robust, Integrated, and Intelligent Design Tools - Enable the availability of a set of robust design tools that are capable of being integrated and interoperable across the enterprise.

> **DoD.D.1.1 Implement AM Design Tools and Software –** Select, mature or develop the appropriate design tools and scale usage across the enterprise to fully enable the unique design capabilities of AM.
>
> **DoD.D.1.2 Integrate Materials, Process, and Property data into Design Tools** – Incorporate materials, process, and property data into design tools to improve design effectiveness.
>
> **DoD.D.1.3 Ensure Intelligent Process Design Tools** – Implement tools that determine optimal build parameters, orientations, and support structures.

DoD.D.2 Enable Design for AM – Establish necessary process, and infrastructure to enable design for AM. This objective helps realize the design synergies that are enabled by AM design methods.

> **DoD.D.2.1 Establish AM Designs/Parts Libraries –** Create AM design repositories (part libraries) for AM parts and ensure availability to all stakeholders and at the point of need.
>
> **DoD.D.2.2 Establish Digital Design Standards –** Build a set of comprehensive rules and standards to guide AM-focused design in a digital context.
>
> **DoD.D.2.3 Ensure Cyber-Physical Security and Anti-tampering –** Develop techniques to ensure that designs are safeguarded throughout the production process and that adversaries are unable to tamper with designs, build files, or machine controls.

DoD.D.3 Improve Reverse Engineering Capabilities – Develop tools, standards, and procedures to mature reverse engineering capabilities for AM sustainment applications.

> **DoD.D.3.1 Standardize Reverse Engineering Procedures** – Create and document a set of uniform procedures for reverse engineering, including tools, software, and equipment.
>
> **DoD.D.3.2 Develop Design Tools for Reverse Engineering –** Develop the design tools necessary to reverse engineer existing part designs, including complex and multi-material parts.
>
> **DoD.D.3.3 Mature 3D Scanning Technologies –** Develop hardware and software capabilities for 3D scanning to enable an efficient and effective reverse engineering process.

DoD.D.4 Develop Design for Function (Application-based Design) Guidelines – Match design needs to AM benefits. Assess requirements and determine how to design components using AM.

DoD.D.4.1 Establish AM Design Rules and Guidelines – Examine AM best practices and lessons learned, leverage understanding to develop AM rules and guidelines.

DoD.D.4.2 Establish AM Materials and Process Selection Guidelines – Create guidelines to govern which materials and processes could be selected to meet which requirements.

7.2 Material Objectives and Technology Elements

DoD.M.1 Define Standard AM Materials Requirements – Understand materials properties as they relate to AM processes and part performance. Determine key characteristics of feedstock materials, and establish standards.

DoD.M.1.1 Establish acceptable AM feedstock material properties – Determine the key characteristics that AM materials must have to meet design requirements and for optimal processing.

DoD.M.1.2 Characterize Impact of Material Properties and Process on Performance – Understand and model the changes in materials performance as properties and process parameters vary.

DoD.M.1.3 Develop Feedstock Materials Specifications and Standards – Develop and document standards to govern feedstock materials, including transport, storage, processing, reuse, recycling, and disposal.

DoD.M.2 Establish Vendor Qualification and Encourage Expansion of Material Sources – Define and apply requirements for the certification of material suppliers to ensure that materials meet all necessary production requirements and encourage expansion of available feedstocks.

DoD.M.2.1 Establish Vendor Qualification Procedure – Create a standard, transparent procedure for qualifying vendors of AM-specific feedstocks.

DoD.M.2.2 Identify Potential AM Materials Sources – Identify capable vendors/sources of AM feedstock materials. Influence development of potential new sources to ensure availability and affordability.

DoD.M.3 Develop AM Materials – Assess currently available AM materials against DoD requirements and develop, as required, novel materials to meet gaps identified for DoD applications.

DoD.M.3.1 Assess Current Materials Capabilities and Identify Gaps – Assess existing AM materials, data and process/property relationships against desired application areas and identify gaps.

DoD.M.3.2 Develop AM Materials to Meet DoD Needs – Develop materials, including novel and non-traditional materials, to meet identified gaps.

DoD.M.4 Create Defined and Accessible Pedigreed Datasets and Schemas – Create high quality, structured and accessible AM datasets. Develop schemas and repositories to collect, format, and house data for broad DoD use.

DoD.M.4.1 Develop Comprehensive and Standardized Material and Process Data Schemas – Develop and document standards and structures for AM data to be housed in repositories.

DoD.M.4.2 Develop Procedures for Pedigreed Datasets – Determine procedures and protocols for verification/validation, access, and ownership of pedigreed datasets.

DoD.M.4.3 Increase the Availability of Pedigreed Datasets – Ensure that data is easily available to relevant stakeholders for continuous enhancement of computer models.

DoD.M.5 Establish a DoD-wide Materials and Process AM Data Repository – Create a living, secure (yet accessible), standardized data repository or repositories to house all material and process AM data.

DoD.M.5.1 Establish Secure, Standardized, Data Repository – Build repositories that can accommodate AM technical data in a systematic, searchable, accessible way across military services.

DoD.M.5.2 Develop Procedures to Populate and Use Data Repository – Create governance processes for access to repositories and standardize data formats for usability.

DoD.M.5.3 Populate Repository with Available Data – Compile available, current data into the database using standard formats/schemas for wide accessibility.

DoD.M.6 Develop Model-based Approaches to Accelerate Materials Qualification and Certification – Develop advanced computational methods to accelerate qualification and certification, for example, by minimizing design and process iterations and by reducing testing requirements.

DoD.M.6.1 Develop Empirical and Physics-Based Models – Develop models to simulate AM materials and processes and predict performance.

DoD.M.6.2 Develop Approaches to Reduce Computation Time – Develop approaches such as reduced order models to reduce computational intensity required for AM materials and processes.

7.3 Process Objectives and Technology Elements

DoD.P.1 Develop NDE and Process Control – Develop and validate process sensing and control technologies and NDE techniques to enable consistent processing and verification of quality.

DoD.P.1.1 Improve In-Situ Process Sensing/Monitoring Capabilities – Optimize current capabilities and develop new sensors to enable continuous, comprehensive process management.

DoD.P.1.2 Develop Closed-loop Process Control – Improve sensor data collection and handling, develop computationally efficient control algorithms, and work with industry to implement closed-loop controls

DoD.P.1.3 Advance Data Collection and Analysis – Develop advanced data collection and analysis techniques that can manage AM process data.

DoD.P.1.4 Develop and Validate NDE Capabilities – Develop approaches for NDE, both post-process and during the build. Validate NDE techniques for material quality and process capabilities.

DoD.P.2 Establish Stable and Robust AM Processes – Enable broader application of AM through process stability and equipment ruggedization.

DoD.P.2.1 Reduce Process Variability – Understand critical process parameters and how to control them to reduce variability.

DoD.P.2.2 Ensure Development of Process Standards and Specifications – Collaborate with standards development organizations and industry to publish process standards that meet DoD requirements.

DoD.P.2.3 Establish Equipment Certification and Calibration Procedures – Develop hardware certification standards and calibration programs that contribute to process stability.

DoD.P.2.4 Improve and Optimize Existing AM Processes – Develop incremental improvements to technologies involved in the production process. Address shortfalls in capability, such as for larger parts, smaller features, increased speed, dimensional accuracy, and precision.

DoD.P.3 Develop Open Architecture Equipment – Advance hardware/software with open interfaces, allowing for monitoring and control of build processes.

DoD.P.3.1 Develop Open-Architecture Platforms – Develop open hardware and software platforms to enable systems integration, such as process control, robotics, variability reduction, etc.

DoD.P.3.2 Ensure Documentation of Open Architecture Standards – Develop and document standards for open architecture equipment.

DoD.P.3.3 Develop Open Architecture Equipment Vendors – Share open architecture learnings with viable hardware and software vendors. Encourage development and availability of open architecture systems to enhance AM capabilities.

DoD.P.4 Modify Existing or Develop New Process Capabilities – Modify existing or develop new AM process capabilities for broader application of AM throughout DoD.

DoD.P.4.1 Develop AM Repair Processes – Modify existing or develop AM capabilities for repair applications (non-AM parts). Assess and address reparability of AM parts.

DoD.P.4.2 Develop Hybrid AM/Traditional Manufacturing Systems – Develop hybrid processing approaches, i.e., those processes that combine additive and conventional techniques.

DoD.P.4.3 Develop Capabilities for Larger Part Processing – Increase capabilities for production of large parts, including continuous build and multi-laser equipment, engaging with industry where appropriate.

DoD.P.4.4 Develop Capabilities for Multi-Scale Processing – Understand issues involved in AM processing at various scales. Develop multiscale approaches that integrate processing for a range of sizes, such as combining functional and structural components.

DoD.P.4.5 Develop Capabilities for Multi-Material Processing – Increase capabilities in multi-material processing, including multi-material feed, post-processing capabilities, and multi-material modeling.

7.4 Value Chain Objectives and Technology Elements

DoD.V.1 Build Cost Models and Decision Tools – Build cost models and decision tools to determine appropriate applications of AM.

DoD.V.1.1 Identify and Capture AM Use Cases and Best Practices for Repair, Part Replacement, and New Part Manufacture – Compile and communicate use cases and lessons learned that provide data points for the feasibility of various AM applications.

DoD.V.1.2 Develop Adequate Cost Models for AM implementation – Develop appropriate cost models that take into account pre- and post-processing and can determine the financial implications of using AM in a given application.

DoD.V.1.3 Develop and Implement AM Decision Tools to Establish the Value Proposition – Develop appropriate decision tools that consider cost and non-cost factors associated with the use of AM.

DoD.V.2 Develop Qualification and Certification Methods for Parts and Systems – Develop methods to qualify and certify AM components, including new, replacement, and repaired/remanufactured parts.

DoD.V.2.1 Understand Risk of AM Approaches – Understand and quantify the risks associated with using AM for DoD parts, both critical and noncritical applications.

DoD.V.2.2 Inform Decision Authorities re: AM Technology – Communicate relevant AM technology capabilities and risks to DoD decision authorities for qualification and certification.

DoD.V.2.3 Ensure Qualification and Certification Methods Accommodate AM Technologies – Determine how best to accomplish qualification and certification for AM components and systems. Recommend any updates to existing policies and procedures.

DoD.V.3 Establish Cyber Infrastructure and Cyber Security – Develop secure information technology infrastructure for end-to-end connectivity of the manufacturing process, i.e., from design to production to service life to decommissioning (i.e. the digital thread).

DoD.V.3.1 Establish Configuration Management for Data Collection and Monitoring – Determine appropriate methods to ensure consistent format and quality of data during data collection.

DoD.V.3.2 Integrate AM Practices into Enterprise-Wide Product Lifecycle Management – Understand integration points for AM within existing product lifecycle management processes and merge AM needs with existing infrastructure.

DoD.V.3.3 Integrate AM with Efforts that are Developing the Model-Based Enterprise and the Digital Thread Infrastructure – Leverage model-based enterprise and digital thread programs that enable the implementation of AM.

DoD.V.3.4 Drive toward DoD Usage of 3D data – Replace standard 2D drawings included in today's tech data packages with 3D models. Advocate requirements for tech data in 3D format and rights to such data, as appropriate.

DoD.V.3.5 Ensure Cyber Security – Ensure that data is protected both internally and across the supply chain, enabling a secure digital supply chain.

DoD.V.4 Establish Physical AM Infrastructure – Plan for and begin implementing AM capability for R&D, production and sustainment across the defense community.

DoD.V.4.1 Assess Current AM Capabilities and Gaps – Evaluate AM capabilities and determine gaps that must be addressed to establish adequate infrastructure.

DoD.V.4.2 Create DoD AM Enterprise Infrastructure Plan – Develop a plan to implement comprehensive AM infrastructure across the DoD.

DoD.V.4.3 Implement DoD AM Enterprise Infrastructure Plan – Carry out the AM infrastructure plan developed for DoD.

DoD V.5 Business Practices – Intellectual Property, Data Rights and Contracting Issues specific to AM

DoD.V.5.1 Issue Guidance on Intellectual Property and Data Rights Considerations – Develop and issue guidance for the consideration of IP/data rights within the business case for AM.

DoD.V.5.2 Create Streamlined Contracting Approaches for AM Parts – Determine how AM can be procured within the existing DoD contracting environment; customize processes and procedures as necessary.

8 KEY TAKEAWAYS

Opportunity of AM - AM offers considerable opportunity to enhance warfighting capabilities and create supply chain efficiencies

Section 4 on Applications outlined the vast opportunity for AM within the DoD. Consensus from participants in the roadmapping workshop was that while AM may have many unknowns and challenges to overcome, the opportunity expected from DoD-wide utilization of AM is great enough to warrant the application of resources and a designation as a "game changing technology."

Synergistic Visions – Shared visions provide an opportunity for coordination on many priorities

The Services and DLA have very synergistic visions for AM development, which provide an opportunity for coordination on the majority of DoD AM objectives. There is also a strong desire to share information, data, and knowledge, and coordinate future investments. The technology "Enablers" identified in Section 5 are also strong opportunities for synergistic action from the services and DLA to enable implementation of AM technology.

Structured Format for Action – DoD AM roadmap provides a major step towards focusing AM technical development strategy

The structured format of the roadmap allows for a common language through which to take further action to include prioritization and allocation of resources while maximizing impact to all DoD stakeholders. The roadmap is the first key step towards fostering DoD-wide collaboration for prevention of duplication of effort and leveraging resources.

9 DOD ROADMAP RECOMMENDATIONS

This integrated DoD Additive Manufacturing (AM) Roadmap provides a foundation and framework for focusing any desired collaboration and coordination of the DoD's activities in AM to systematically and efficiently mature the technology for multiple DoD applications. Individuals and organizations may utilize this strategic document to identify areas of focus and address roadmap objectives and technology elements together, where appropriate and beneficial.

By "traveling the roadmap" and working shared objectives together, the national defense destination is improved logistics, new and improved products, and increased materiel readiness from applying this "game changing" technology. Typical of any disruptive technology, AM can be used to our advantage, and our adversaries can use it against us. Speed of travel to implement the AM roadmap becomes an important factor that can be best achieved by coordinating national defense resources to achieve the DoD's shared objectives.

STEP 1: Further Refinement and Development – Create a coordinated DoD-wide plan for advancing AM capabilities

The development of a detailed, tactical DoD-wide AM coordination plan is beneficial for speeding the advancement of AM capabilities. The plan should focus on concrete and coordinated actions to achieve the integrated objectives set forth within the DoD roadmap. To achieve this critical next step, a strong recommendation is for the development of a Lead Integrator and supporting team to champion and lead this effort. Having this role assigned and resourced will help maintain momentum and focus. The supporting team must involve all stakeholders – R&D, engineering, test, logistics, quality assurance, inventory management, maintenance and sustainment, and operating/end users. To enable this coordination, a DoD-wide and DoD-only information sharing mechanism is recommended, such as a Community of Practice/Community of Interest. The sharing mechanism developed should build upon best practices developed within existing groups.

STEP 2: Initial Execution – Begin the execution of the DoD-wide coordination plan for developing AM capabilities

The Services and DLA are currently conducting many activities which are contributing to delivering specific objectives outlined within the joint DoD AM roadmap. This information should be captured and disseminated to other DoD stakeholders for greater awareness. Integrated objectives may be prioritized based on impact to the DoD and resources needed to achieve the objective. Prioritized initiatives may then be defined in more detail with appropriate partners and resources. Commitment is required to achieve the technology objectives as well as the "Enablers" identified in Section 5.

STEP 3: Continuous Improvement – Sustain the development of AM capabilities across the DoD and refine the DoD AM roadmap as AM technology matures

It is recommended that the Lead Integrator periodically coordinate revisions to the DoD AM roadmap to reflect changing priorities, maturing technology, and through gathering the most recent input from all stakeholders. Progress towards achieving the key national defense objectives should be documented, including progress towards achieving the desired impact on capability/readiness and reduced cost using AM.

One additional recommendation is respectfully offered. The Senate "National Defense Authorization Act for Fiscal Year 2017 Report" dated May 18, 2016 includes "Additive manufacturing recommendations" under "Items of Special Interest." The text includes a Senate request for a report from the Secretary of Defense on additive manufacturing and identifies specific details to be addressed. This Integrated DoD AM Roadmap is an important resource which may be utilized to address some of the details requested.

10 POINTS OF CONTACT

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12 APPENDIX: DOD AM ROADMAP TRI-FOLD BROCHURE

KEY ENABLERS TO CONSIDER

The present roadmap development effort focused on AM technology, but through the roadmapping workshop process, participants identified several non-technology enablers that are critical to effective rollout of AM across DoD:

Data Management
Developing the policies, architectures, and procedures to properly manage massive, multimodal AM data.

Policy Change
Modifying organizational governance to realize the benefits of AM.

Cultural Change
Increasing knowledge of and comfort with AM, driving institutional acceptance.

Workforce Development
Readying the DoD workforce (acquisition, R&D, manufacturing, etc.) with the skills to harness AM.

RECOMMENDATIONS

- **Development**
  Create a coordinated DoD-wide plan for for advancing AM capabilities.
- **Initial Execution**
  Begin the execution of the DoD-wide plan for developing AM capabilities.
- **Continuous Improvement**
  Sustain the development of AM capabilities across the DoD and refine the approach to enhance flexibility and optimize ROI.

Context:

This information is based on the integrated DoD AM Technology Roadmap that was developed by USAF, US Army, DON, and DLA personnel participating in a series of participant-driven exercises led by America Makes on May 11th, 2016.

The group integrated objectives from their individual Service-level roadmaps into joint DoD objectives and corresponding technology elements, based on four focus areas. This infographic presents those integrated objectives in a novel format to emphasize overlap.

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View and download at:
AmericaMakes.us/dod-amroadmap

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About America Makes

America Makes is a public-private partnership with a mission to accelerate the adoption of additive manufacturing technologies and increase U.S. manufacturing competitiveness.

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DoD Integrated Additive Manufacturing (AM) Technology Roadmap

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STRATEGIC ALIGNMENT

The DoD's strategic goals – as articulated in the 2015-2018 Strategic Plan — are directly supported by the benefits of Additive Manufacturing (AM).

DoD Strategic Goals	Benefits of AM
Defeat our Adversaries, Deter War, and Defend the Nation	Facilitate adaptive responses and new capabilities to counter increasingly agile adversaries
Sustain a Ready Force to Meet Mission Needs	Use AM to create a more resilient supply chain and enable in-theatre manufacturing
Strengthen & Enhance the Health & Effectiveness of the Total Workforce	Enable cost-effective personalized products and therapies to increase warfighter health
Achieve Dominant Capabilities through Innovation & Technical Excellence	Increase system availability (readiness), and Produce novel, high performance parts
Reform & Reshape the Defense Institution	Incorporate supply chain and production benefits of AM into DoD operations

KEY TAKEAWAYS

Opportunity of AM
AM offers considerable opportunity to enhance warfighting capabilities & create supply chain efficiencies.

Synergistic Visions
Shared visions provide an opportunity for coordination on many priorities.

Structured Format for Action
DoD AM roadmap provides a major step toward focusing AM technical development strategy.

Focus Area	Integrated Objective	Integrated Impact Statement
DESIGN drives technological advancements in new non-proprietary design methods and tools. These tools and methods are required to enable a culture change and break the cycle of designing AM parts like cast or machined parts.	DoD.D.1 – Enable Robust, Integrated, and Intelligent Design Tools	*Streamline design process, reduced cycle time, and higher performance products*
	DoD.D.2 – Enable Design for AM	*Increase capability rapidly delivered to warfighter*
	DoD.D.3 – Improve Reverse Engineering Capabilities	*Push AM forward, enabling increased self-sufficiency of units and innovation by users in the field*
	DoD.D.4 – Develop Design for Function (Application-based Design) Guidelines	*Apply AM to meet specific weapons systems requirements*
MATERIAL builds the body of knowledge for benchmark AM property characterization data and eliminating variability in "as-built" material properties. It also focuses on accelerating advanced material development through computational modeling and advanced simulation.	DoD.M.1 – Define Standard AM Materials Requirements	*Enhance predictability of resulting part performance using an interoperable framework for AM at DoD*
	DoD.M.2 – Establish Vendor Qualification and Encourage Expansion of Material Sources	*Increase the range of materials available to designers, enhancing part performance*
	DoD.M.3 – Develop AM Materials	*Establish priorities for AM material development activities necessary to meet DoD requirements*
	DoD.M.4 – Create Defined and Accessible Pedigreed Datasets and Schemas	*Establish authoritative data sets for simulation and reference*
	DoD.M.5 – Establish a DoD-wide Materials and Process AM Data Repository	*Establish a single repository of material, process, and performance data. Speed up research, enable quality*
	DoD.M.6 – Develop Model-based Approaches to Accelerate Materials Qualification and Certification	*Guarantee quality of AM parts*
PROCESS drives technological advancements that enable faster, more accurate, and higher detail resolution additive manufacturing machines with larger build volumes and improved "as-built" part quality.	DoD.P.1 – Develop NDE and Process Control	*Enhance the sensing capability of machines, gather data to ensure quality*
	DoD.P.2 – Establish Stable and Robust AM Processes	*Enable broader application of AM through process stability and equipment ruggedization*
	DoD.P.3 – Develop Open Architecture Equipment	*Ensure transferability and interoperability through specifications and standards*
	DoD.P.4 – Modify Existing or Develop New Process Capabilities	*Modify or develop processes to increase the applicability of AM in a variety of situations*
VALUE CHAIN encourages technological advancements that enable step change improvements in end-to-end value chain cost and time to market for AM produced products.	DoD.V.1 – Build Cost Models and Decision Tools	*Understand when, where, and how to apply AM*
	DoD.V.2 – Develop Qualification and Certification Methods for Parts and Systems	*Guarantee quality of parts and interface with existing/new DoD policies*
	DoD.V.3 – Establish Cyber Infrastructure and Cyber Security	*Enable secure information technology infrastructure for end-to-end connectivity of the manufacturing process*
	DoD.V.4 – Establish Physical AM Infrastructure	*Install AM machines across DoD enterprise*
	DoD V.5 – Business Practices – Intellectual Property, Data Rights and Contracting Issues specific to AM	*Establish agreed-upon business practices to ensure seamless integration of AM into the existing supply chain*