


Additive Manufacturing Technology Roadmap for Casting and Forging

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1 Executive Summary

Cast and forged components lie at the heart of critical weapons platforms across the Department of Defense (DoD), providing a vital contribution to warfighter readiness for the United States. With a 67% reduction in the number of US foundries since 2000, the US Castings and Forgings (CF) ecosystem supply chain is dwindling. Accounting for offshoring and persisting economic headwinds, the remaining high-quality domestic purveyors of castings and forgings tend to prioritize high-quantity orders and customers. This problem is particularly exacerbated by the nature of legacy platforms, whose designs and processes were largely conceived, defined, and stored on paper. In tandem with the pervasive challenge of workforce availability, the challenges for the DoD to acquire low-volume cast and forged components pose a critical and enduring issue amid geopolitical turmoil.

This report defines a multi-year technology roadmap to develop and deploy Additive Manufacturing (AM) capabilities at scale to augment existing CF operations. The use of advanced technology, particularly that which poses compelling advantages at low production volumes, unlocks a crucial capability for the Defense Industrial Base (DIB) to respond to warfighter needs rapidly and in an economically viable manner. There are many examples of AM's benefit in principle and a few in practice, developed within siloed pockets of expertise over numerous years and at significant cost. This effort recognizes the timebound need to rapidly scale AM capabilities out of the lab, beyond proof of concept, and onto shop floors nationwide. America Makes is poised to lead the way in delivering these capabilities at scale.

The roadmap has been intentionally shaped to be broadly applicable yet meaningfully specific. It has been structured for use across two manufacturing industries and all military branches, with products of nearly all risk levels, materials, sizes, and applications having been considered. The complexity of AM has been overlaid with these spaces to identify what sits at the intersection of need and capability, charting a path forward for how it can be achieved. These layers were navigated through a three-phased approach to gather data, construct execution plans, and validate the path forward. Diverse sets of experts across the CF and AM ecosystems representing Government and Industry stakeholders were strategically convened at each phase and across geographical regions. Extensive data collection from these collaborations has been supplemented by and compared against academic literature searches, subject matter expert interviews, production site visits, and DoD order data.

The roadmap comprises a portfolio of 21 projects and their execution plans over a 57-month duration. The underlying strategy is focused on deploying technology at scale. Within its scope, 40 material-process combinations and 52 individual components are assessed alongside 25 demonstrations to transfer key outcomes and five pilots to perform stress tests in production environments.

To realize the capabilities identified through this process, investment is required in four critical areas:

Scale Current State:
This group of projects aims to disseminate established technology beyond siloed pockets of expertise. The capabilities that these projects promote tend to be more mature compared to the Prove Production Capability Swim Lane

Prove Production Capability:
This group of projects seeks to mature demonstrated and emerging technology to meet production needs predictably. The capabilities that these projects promote tend to be less mature compared to the Scale Current State Swim Lane

Build Digital Foundation:
These projects will help establish an infrastructure for components and simulation models to drive agility and accelerated design cycles. As the name describes, these projects are foundational for the future deployment of advanced manufacturing technologies across the Defense and Organic Industrial Bases (DIB and OIB)

Supporting Efforts:
These projects centralize common activities across the projects in other swim lanes to drive the adoption of the developed capabilities. These projects standardize documentation, drive efficient delivery, and strive to build awareness and competency across the DIB and OIB

Through the roadmap and the process of crafting it, America Makes has gained valuable insight into how development and funding should be positioned and delivered to impact casting and forging supply chains. With a path forward established, continued, and sustained investment is required to ensure that warfighter readiness is enabled by arming the CF ecosystems with accessible and capable AM solutions. To realize a broad and enduring national capability, continued focus is required to ensure technology development is transferred from demonstration to production, realized through three key next steps:

Lower Adoption Risk	While the benefits and potential of AM are well known, so are many examples of failed printing pilots. Many risks driving these failures are seemingly hidden as they sit adjacent to the printing process. Providing small and medium manufacturers with resources to make informed decisions on when to use AM and to upskill staff without major financial investment will support the broader adoption of AM technologies.
Invest in Technology Deployment	Implementing AM successfully requires much more than a capable printer. Continued focus on transferring key outcomes out of the lab and onto the shop floor is crucial to drive familiarity with AM and create true learning environments for users. Guidance for everyday process control should be established and provided as oversight to onboard new technology.
Incentivize Expertise	Early adopters of AM have significantly invested in developing their internal capabilities and intellectual property. These key examples have the potential to be replicated at scale but can only be done so by establishing incentives for knowledge sharing.

These areas are the “No Regrets Next Steps” necessary for the long-term success of an AM-augmented, agile, and resilient supply chain for the DoD.

2 Background & Objectives

2.1 Background

In February 2022, the DoD published a strategic roadmap to address supply chain vulnerabilities within the DIB. Within the scope of work, castings and forgings were listed as one of the four most critically vulnerable focus areas, posing immediate national security risks if these vulnerabilities remained unaddressed. The DoD tasked America Makes with developing a strategic technical roadmap to define how AM technologies can augment challenges within the castings and forgings supply chain that affect mission readiness for critical platforms.

America Makes is the nation's leading and collaborative partner in AM technology research, discovery, creation, and innovation. As the flagship Manufacturing USA Institute, America Makes is the trusted source of information for the AM community. Through a network of members and partners, the Institute incubates and supports the commercialization of innovative technologies critical to the next wave of AM innovation and technology adoption. In doing so, the Institute is contributing to the revitalization and reinvigoration of the American manufacturing sector and is perfectly positioned to oversee the development and execution of a national AM strategy for augmenting CF supply chains.

2.2 Objectives

The overarching objective of this effort was to convene the US AM ecosystem, along with the US domestic CF ecosystem, to identify opportunities and build a corresponding roadmap to augment traditional CF production with AM. To date, there has been limited exploration of broad production use, with efforts primarily resulting in direct printing replacements or siloed pockets of expertise. A more strategic assessment was needed to define the space and necessary investment for AM to make a meaningful impact in the short term and in production facilities across the country.

> *"Keeping pace with technological change should not be the capability of a few, or an over-the-horizon goal, out of reach for most of our manufacturing base. It should be a pillar of American industrial competitiveness"*

Specifically, the construction of the roadmap was focused on the CF technology domains and its outcomes aimed at generating impact by supporting warfighter readiness through cost-effective, low-volume production, driving supply chain resilience with technology-driven agility and flexibility, and improving labor efficiency across process steps. To achieve this, the project was centered around three key objectives:

- Identify the major issues affecting CF supply chains and their common characteristics
- Prioritize and map AM opportunities to those issues, defining the scope and investment required
- Determine what infrastructure is needed to address the challenges defined

AM encompasses a broad and evolving space. Therefore, the strategic direction was further shaped by focusing these objectives on specific areas. First and foremost, the project sought to identify the most impactful means to support CF supply chains, considering direct part replacement while looking broadly across processing steps. Secondly, all CF processes (e.g., sand casting/investment casting, open die/closed die forging) were considered equally, guided by data, and based on potential impact. To drive short-term and scaled impact, new and functionally graded materials and nascent technologies were not considered. Lastly, as a technically focused roadmap, re-engineering the bidding and acquisition process was deemed out of scope. While not included in the resulting roadmap, key non-technical takeaways are discussed in Section 7.2.

3 Approach

3.1 Approach Overview

A three-phased approach was defined to transform today's CF ecosystem's challenges, opportunities, and experience into a forward-looking roadmap to implement AM augmentation at scale. The Discovery, Functional Analysis, and Synthesis phases were executed over eight months and collectively generated, structured, and synthesized raw data into the final strategic roadmap. A visual of the overall approach is depicted in Figure 1.

The Discovery phase laid the groundwork for the project by building a comprehensive picture of current and future states and defining goals to close the gap between them. Strategic communications channels and materials were established to convene the broad spectrum of experts across the casting, forging, and AM ecosystems; this included the creation of an Advisory Board comprised of Government and Industry stakeholders. Data was gathered through multiple sources, including academic literature, interviews with subject matter experts, and site visits. Numerous perspectives were considered and actively measured to ensure diversity of opinion across casting, forging, and government. Additional details on the data-gathering approach are specified in Sections 3.1.1, 3.1.2, and 3.1.4, with insights from the data included in Section 4.1.

The Discovery phase culminated in the Visioning Workshop, which narrowed the vast opportunity space down to a set of goals for achieving future state.

The Functional Analysis phase leveraged the gaps and goals identified during Discovery to generate detailed and prioritized execution plans, which serve as primary elements of the roadmap. This transformation of directional goals into detailed plans was performed in the Functional Analysis Workshop, where experts across the convened ecosystems were selectively grouped to define cost, duration, and key metrics. Initial prioritization of the project set was performed based on each project’s expected difficulty, impact, and applicability across materials. Additional detail on the workshop approaches across phases is discussed in Section 3.1.4. Insights from the workshops, including summarized output, are detailed in Section 4.2.

Finally, the Synthesis phase leveraged the execution plans to structure CF roadmaps and the necessary investment to fund them. Focused feedback on the grouping, sequencing, and execution plans for the

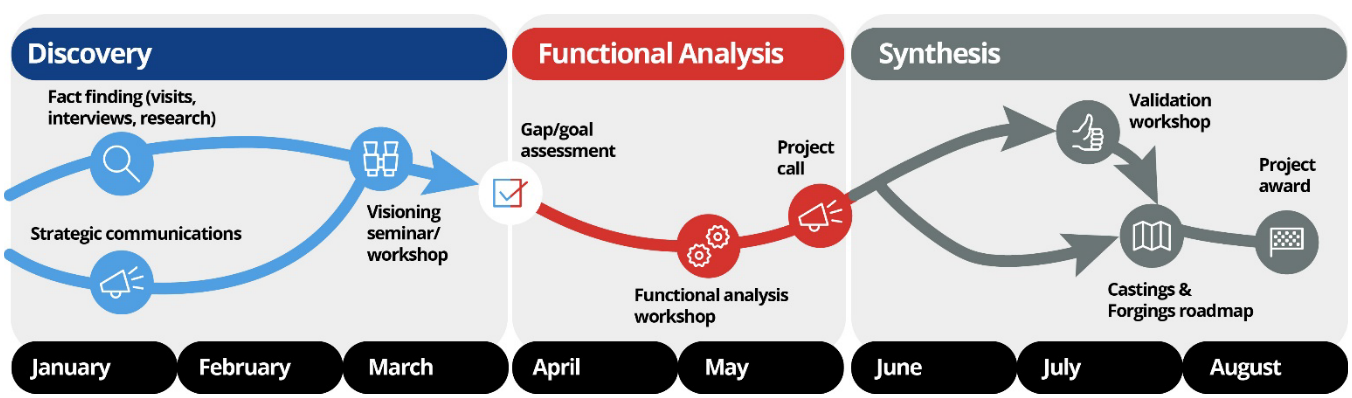


Figure 1: Three-Phase Project Approach

constituent projects was performed in the Validation Workshop. A focused group of subject matter experts, alongside project sponsors, provided feedback to refine and finalize the roadmap elements.

3.1.1 Literature Review

Academic literature was reviewed to provide data on key areas of interest for casting and forging related AM research. Combined with findings from interviews with subject matter experts, the data was analyzed to identify potential applications of AM in CF production settings that academic research has not addressed, as well as whether these efforts are suitable to address the challenges of sourcing castings and forgings for the DoD.

To perform this analysis, over 400 articles were pulled and sorted based on relevance, leaving 102 articles to analyze. A bibliography from the review is contained in Appendix H. The remaining articles were categorized into a hierarchy of topics, sub-topics, and the associated materials and processes of interest. The papers were gathered through an online search using keywords to return results that studied AM and focused on castings and forgings. The data was compared against similarly structured data collected during interviews, identifying gaps and overlaps between the two as input to the later workshops.

The topics and subtopics were initially defined to span the entire process flow and lifecycle, from design to part qualification. As the literature was reviewed, the topics and subtopics were iteratively expanded and refined through a peer review while categorizing each paper within the updated framework. The resulting set of eleven topic areas is detailed in Table 1.

Table 1: Literature Review Topic Areas

Topic Area	Description
AM Process Optimization	Incrementally improve the capability and stability of existing printing process(es)
Casting and Forging Augmentation	Apply AM to produce ancillary components (e.g., wax patterns) and tooling
Design Optimization	Improve design performance with computational optimization
Digital Capability/Industry 4.0	Improve data analysis capabilities leveraging advanced 3D tools, parallel computation, and artificial intelligence
Hybrid Manufacturing	Integrate AM and traditional processing within one process step (e.g., interpass forging)
In-Process Monitoring	Formulate pipelines and analysis techniques for layer-wise data gathered during printing
Material Performance Characterization	Test performance and effect of material processing parameters on key material properties
Non-Destructive Testing	Improve resolution and fidelity of techniques to predict material and part performance
Novel Materials	Formulate and test customized material systems (e.g., functionally graded and metamaterials)
Part Qualification	Define and compare frameworks to assess predicted part performance against requirements
Technology Overview	Meta-analysis of broader sets of related studies

Within this set of topics, 53 subtopics were defined to differentiate the studies at a more detailed level. The Casting and Forging Augmentation topic and the corresponding subtopics are detailed in Table 2 as a representative example. The complete mapping of subtopics is detailed in Appendix A.

Table 2: Representative Topic-Subtopic Mapping

Casting and Forging Augmentation
- Printed Sand Molds
- Printed Tooling
- Conformal Cooling
- Printed Patterns and Shells
- Near-Net Shape Parts

In addition to structuring the topics addressed by each study, the associated materials and processes of focus were also recorded. Where possible, this information was logged for both AM and CF contexts. This resulted in AM-related data covering 37 materials and five process modalities and CF-related data covering five materials and six process modalities. Analysis and insights from the collected data are discussed in Section 4.1.1.

3.1.2 Interviews

Interviews with subject matter experts were conducted to gain insight into the current and potential future states of DoD-sourced castings and forgings. Interviews served as critical sources of information, where each discussion was structured for collective analysis to identify trends in individual process modalities across Government/Industry perspectives and within CF/AM ecosystems. These findings combined with those from the literature review to produce the initial input to the Visioning Workshop.

The team interviewed a diverse set of 39 subject matter experts who represented 29 organizations across Government, Industry, and research perspectives.

Data gathered within each interview was structured using a coding methodology, which categorized individual data points from the discussion within a coding hierarchy. The highest level of the hierarchy (L1) consists of three categories:

- **Pain Points:** Current challenges in today's operational environment
- **Opportunities:** Potential solutions to current challenges that utilize AM
- **AM Shortcomings**: Limitations of current state AM technology to realize opportunities

Within each high-level category, two additional levels of sub-categories were defined (L2 and L3, respectively) to address different stages of the value chain at a more granular level. Figure 2 through Figure 4 depict the coding hierarchies for pain points, opportunities, and AM shortcomings, respectively. Definitions for each code can be found in Appendix G.

The pain point codes were grouped into five L2 codes, as shown in Figure 2. Supplier Management encompasses the challenges of meeting certification requirements and handling low-volume orders. The L2 regarding People refers to the available labor supply and challenges of knowledge retention and upskilling. Operations L2 codes address the process flow surrounding the primary manufacturing process, while Material and Process pain points cover difficulties within the process itself, such as low yield or process capability. Digital Infrastructure combines data management issues with the need for digital design information.

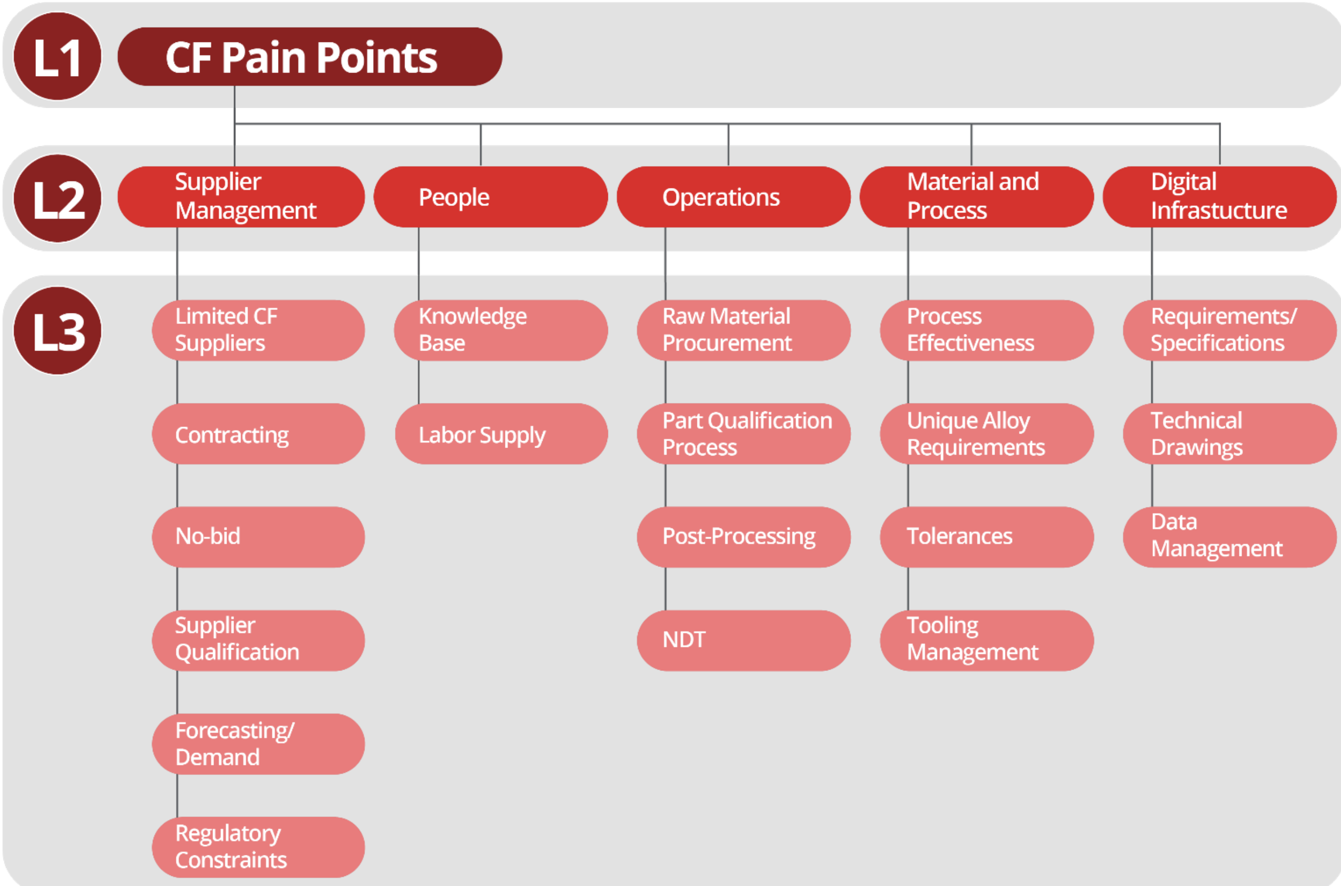


Figure 2: Code Hierarchy: Pain Points

The opportunity codes were grouped into five L2 codes, as shown in Figure 3. The first three L2 categories (Tooling, Hybrid Manufacturing, and Direct Printing) demonstrate how AM can be directly utilized. Digital and Workforce Development categories address opportunities where AM is indirectly deployed to improve throughput. Capabilities for Tooling include printing molds and repairs to allow processes to flow consistently. Hybrid Manufacturing combines AM with CF to reduce production steps and advance part design. Direct printing explores the potential for prototyping and replacement by using AM parts. The digital opportunities aim to address the digital infrastructure pain points by utilizing modeling solutions to improve the part approval process. The workforce development pipeline opportunities alleviate labor challenges within the casting and forging industries and improve the knowledge required to introduce new technologies.

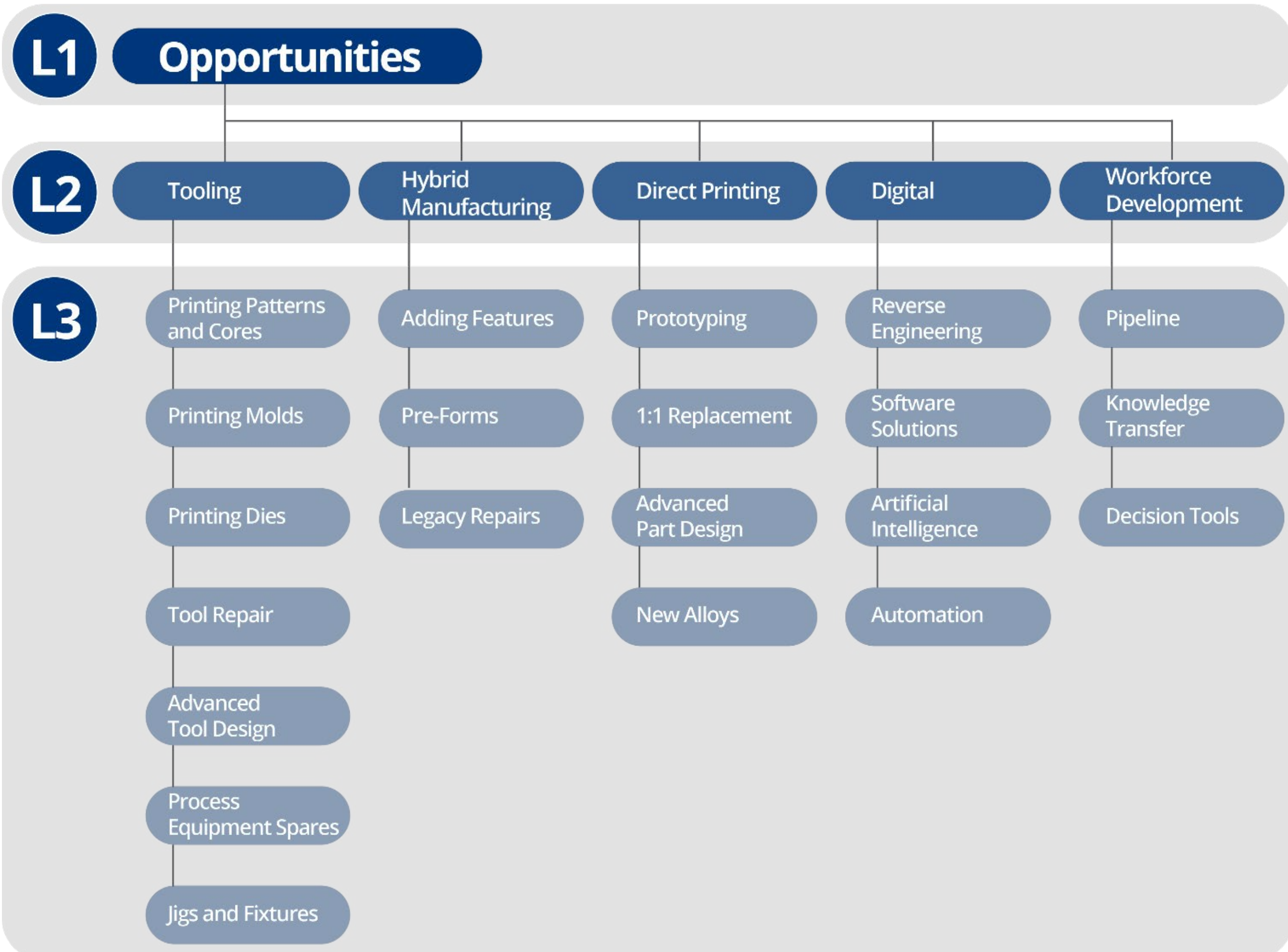


Figure 3: Code Hierarchy: Opportunities

The AM shortcomings codes were grouped into six L2 codes, as shown in Figure 4. AM Qualification codes are AM Shortcomings that refer to the challenges of introducing novel technology into long-standing acceptance processes. Material Performance concerns the properties and finish (consistency, finish, holes, etc.) of the material produced by AM processes. Post-processing refers to challenges with necessary operations downstream of printing. Technology Limitations define constraints of commercially available AM solutions and misalignments between current capability and DoD needs. Business Constraints refer to the everyday economics, education, decision-making, and regulations that may limit or halt the continued use of AM by small and medium manufacturers. Finally, Industry Maturity refers to the broader maturity of AM, which continues to see the growth of printer manufacturers, material providers, and overall use of the technology in industrial settings.

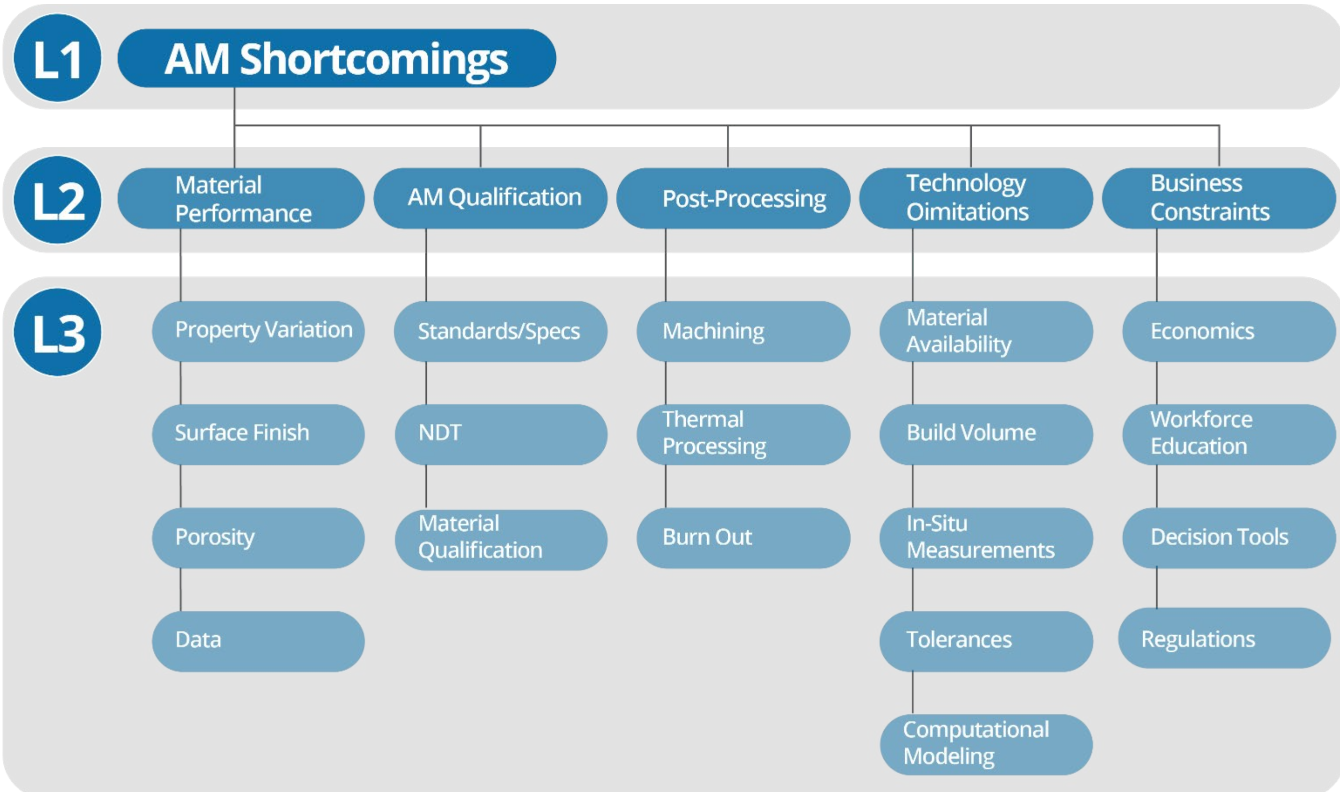


Figure 4: Code Hierarchy: AM Shortcomings

Given the technical nature of the roadmap, it was essential to scope the interview data when preparing for the Visioning Workshop. The literature review and interview synthesis data were distilled into detailed inputs for the Visioning Workshop. The workshop inputs are outlined in Appendix B.1. Deloitte conducted an initial focus area assessment that was reviewed and finalized with the Advisory Board. When determining focus areas within the pain points, each code was assessed against the roadmap's goal and the likelihood that a technical opportunity could alleviate the pain point. For opportunity codes, focus area determinations were based on the overall project scope and the opportunity's time horizon. With AM shortcoming codes, considerations dependent on the printer manufacturer are not in scope for the roadmap because there was no intention to define new AM materials or technologies. The focus area assessments and additional details can be found in Appendix B. Additional insights on the categories that were not focus areas for the Visioning Workshop can be found in Section 7.2.

3.1.3 Strategic Communications and Stakeholder Participation

Convening a broad set of diverse stakeholders was critical to developing a roadmap that meaningfully addresses the challenges of sourcing low-volume DoD castings and forgings. Specifically, it was necessary to have participation from the CF and AM communities alongside Government and Industry perspectives. To address this need, a strategic communications plan was deployed to:

- Accelerate collaboration across the end-to-end CF supply chains
- Drive participation and data generation in workshops

- Establish a Government and Industry Advisory Board for strategic guidance across phases
- Enhance the overall impact of the roadmap by building trust through its creation
- Increase broader community awareness of the efforts to speed up casting and forging throughput with AM

Leveraging America Makes' broad reach and extensive network, the Advisory Board was established through a targeted outreach program and convened monthly to provide targeted and regular guidance. The organizations represented on the Advisory Board are detailed in Table 3.

Table 3: Government and Industry Advisory Board Organizations

Government
- Air Force Lifecycle Management Center (AFLCMC)
- Air Force Research Laboratory (AFRL)
- Defense Logistics Agency (DLA)
- Office of Naval Research (ONR)
- Office of the Secretary of Defense (OSD)
- U.S. Army
- U.S. Navy

Industry
- American Foundry Society (AFS)
- Forging Industry Association (FIA)
- Investment Casting Institute (ICI)
- North American Die Casting Association (NADCA)
- Steel Founders' Society of America (SFSA)

The strategic communications and outreach plan determined how to define key participant groups and drive workshop attendance across them. The detailed steps within the approach are discussed below and depicted visually in Figure 5.

1. **Establish Qualifications for Desired Attendees**: The team collaboratively identified the qualifications and expertise desired from prospective participants. These desired qualifications were then confirmed among the Industry Advisors, who leveraged their networks to suggest the names of prospective attendees
2. **Develop and Leverage Outreach Resources**: Materials were developed to include a one-page workshop fact sheet, a workshop road-show presentation, and outreach email templates that the Industry Advisors leveraged when pitching prospective participants to attend the workshops.
3. **Execute Targeted Outreach**: The Industry Advisors and America Makes executed outreach, using the developed resources, to the agreed-upon contacts
4. **Complete Availability Survey**: Once prospective participants had been pitched to attend, they were provided a survey to complete that captured their experiential information as well as their availability to attend both sessions of the workshops (See Appendix C for survey questions)
5. **Distribute Save the Dates**: After participants indicated their availabilities, they were sent a 'Save the Date' with relevant workshop information
6. **Ongoing: Update Workshop Participant Matrix:** As workshop attendees completed the availability survey, the project team updated the participant stakeholder matrix to track event attendance and highlight target attendees who needed additional follow-up

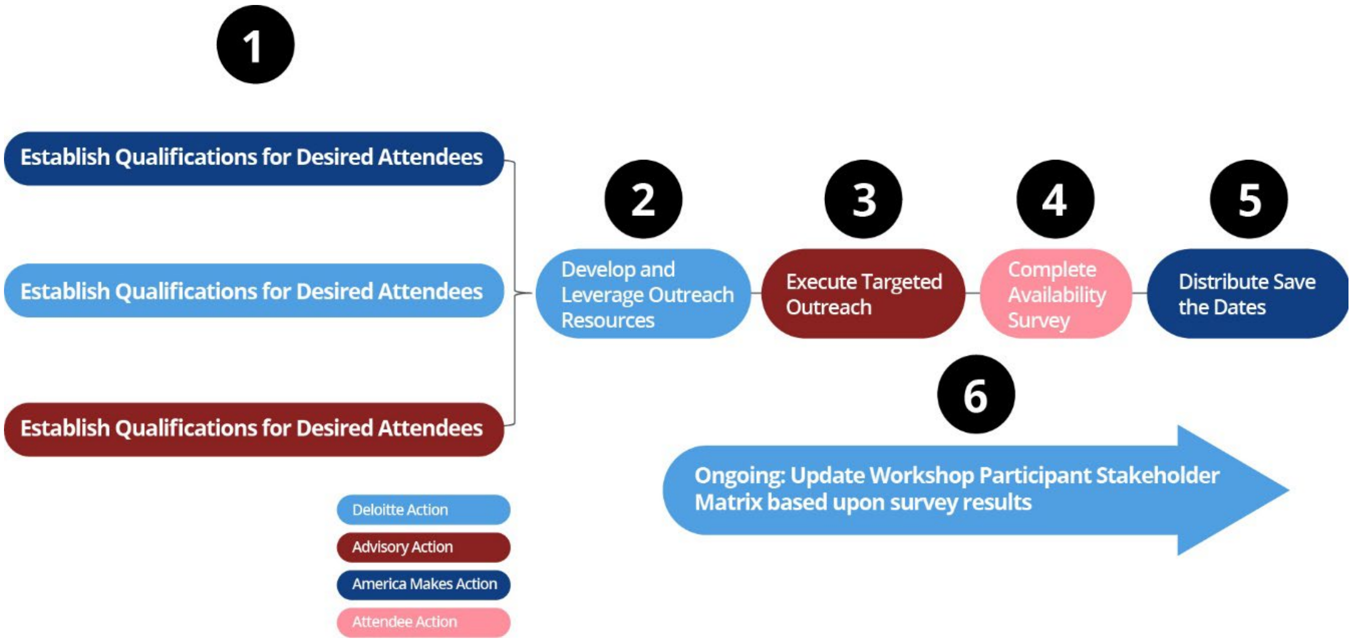


Figure 5: The Strategic Communications and Outreach Plan

After defining the desired participants from Step 1, a stakeholder matrix was developed to track the attendance of individual project participants within each targeted area of expertise. The targeted stakeholder groups included the following:

- **Casters:** Comprised of stakeholders representing small and medium-sized business owners, metallurgists, and operators in the casting industry while covering multiple casting processes (i.e., sand casting, investment casting, die casting, permanent mold, etc.)
- **Forgers:** Included similar subject matter experts (i.e., small to large business owners, metallurgists, etc.) with experience crossing open die forging, closed die forging, and ring rolling forging processes
- **Additive Manufacturers:** Included experts from the AM business community with experience in printing sand, ceramic, and wax materials, as well as process experience with directed energy deposition (DED) and Laser Powder Bed Fusion (LPBF)
- **Academia:** Comprised of professors from higher education with experience in academic research and authoring studies in the CF and AM disciplines
- **Original Equipment Manufacturers (OEMs):** Included representatives from prime contractors who subcontract work out to the casters and forgers and bring a customer's perspective to the current supply chain challenges
- **Government:** Included members of the military and civilian representatives from the DoD, as well as representatives from OIB, with knowledge of the agency's procurement processes, manufacturing processes, and part-performance requirements

Target participation from each group was set leveraging America Makes and the Advisory Board and subsequently integrated into the stakeholder matrix for continuous monitoring ahead of each workshop. Table 4 details these targets and the diversity of participation within the final stakeholder matrix.

Table 4: Workshop Participant Stakeholder Matrix

Workshop Attendee Targets and Confirmation by Stakeholder Group					
Communities	**Targets**	**Milwaukee Mar 16**	**Youngstown Mar 29**	**Youngstown May 10**	**Milwaukee May 17**
Investment Casting	1–3	2/3	4/3	3/3	4/3
Die Casting	1–3	5/3	2/3	0/3	1/3
Sand Casting	1–3	7/3	5/3	2/3	4/3
Other (Permanent Mold, Centrifugal Casting)	1–3	1/3	4/3	1/3	0/3
Open Die Forging	1–3	3/3	3/3	2/3	2/3
Closed Die Forging	1–3	2/3	2/3	1/3	1/3
Ring rolling Forging	1–2	3/2	1/2	1/2	1/2
AM Businesses & Experts (sand, ceramic and wax printing, DED, and LPBF)	5–7	4/7	9/7	19/7	5/7
Academia	3–5	4/5	6/5	4/5	3/5
Associations & Standards Development	4 – 6	5/6	5/6	7/6	5/6
OEM Representatives	6 - 10	7/10	6/10	2/10	3/10
Government	6 - 10	3/10	9/10	8/10	7/10
Totals	**~30 - 50**	**52/55**	**57/55**	**72/55**	**54/55**
Actual		**47**	**48**	**50**	**36**

The Strategic Communications and Outreach effort created a significant positive impact by:

- Communicating to the prospective participants how the road-mapping effort addresses critical national security implications and guides future investments into the casting and forging industries
- Developing and implementing a process to secure workshop attendance from a diverse set of participants that led to more robust insights and more sustainable long-term outcomes
- Capturing relevant participant experiential data to inform workshop activities and groupings when participants were split into breakout groups
- Instilling confidence across CF and AM communities in the road-mapping approach

More than 250 prospective attendees were contacted, and more than 150 completed the availability survey. The project team's original attendance goal was 30 participants at each workshop, and each session had at least 36, surpassing the attendance goal and allowing the team to capture more insightful data that has informed the findings of this roadmap. Figure 6 recognizes and praises the participation of the organizations represented by the workshop attendees.

Figure 6: The Subject Matter Expert Ecosystem

3.1.4 Workshops

Workshops were structured to gather comprehensive data representing a broad diversity of opinions across casting, forging, and AM ecosystems. Subject matter experts were convened in person to collaboratively identify and construct potential solutions, leveraging their broad spectrum of specialized process knowledge (e.g., sand casting or investment casting). Within the Discovery and Functional Analysis phases, each workshop was held twice and in different locations (Youngstown, Ohio and Milwaukee, Wisconsin) to maximize participation and capture regional expertise. The Validation Workshop was held virtually with a focused group of Government Advisors.

Data was generated by facilitating tailored breakout groups of these subject matter experts and guiding discussion through structured exercises. Discussions were not facilitated to reach a consensus within each breakout group; a difference of opinion was treated as an opportunity to gather deeper insight, with details captured to the greatest extent possible. Following each workshop, the data collected was transcribed into a structured, digital format.

Workshop data was synthesized using a structured process:

1. **Combine** datasets across workshops
2. **Code** raw data into a common set of categories
3. **Compare** trends across ecosystems and specializations
4. **Capture** insights as input to next steps

Insights were documented in workshop summary reports and presented to the Advisory Board for feedback and strategic guidance, ensuring that the broader direction and specific details were validated at each of the project's phases.

Summary reports were also leveraged to support future America Makes project calls. Each report was modified and submitted for Distribution A approval to share with organizations participating in the workshops, driving interest and mutual benefit for participating.

3.1.4.1 Visioning Workshop

Visioning Workshops served to translate initial findings from the literature review and interviews into structured goal statements driven by participant input. To arrive at these goal statements, the pain points, opportunities, and AM shortcomings documented throughout Discovery were utilized as raw material for a cyclical process of ideation and prioritization. The process was designed to guide participants to generate detailed views of current and future state, with goal statements bridging the gap between them. The process addressed the following areas:

1. **C&F Pain Points**: What are the supply chain and manufacturing pain points that are driving long lead times for castings and forgings?
2. **Opportunities**: What are some of the ways we can address the casting and forging pain points using AM or other advanced technologies?
3. **AM Gaps**: What are the gaps with AM/other advanced technologies keeping us from adopting this opportunity today?
4. **Goal Statements**: Generate concise and deliberate goal statements needed to reach the opportunity
5. **Process & Material Mapping**: What combination(s) of processes and materials will be positively impacted by achieving the goal in question?

The ideation step of the process was designed to collaboratively generate a multitude of concepts, using the prior findings from literature reviews and interviews as starting points to elicit discussion. For example, documented pain points were provided for each breakout group to validate, add to, or remove, with the sets provided tailored to casting or forging-specific discussions.

Prioritization was performed by weighted voting within each breakout group, with participants able to assign higher priority with a higher weight. The results were tallied and sorted to indicate relative priority, with a cutoff imposed to drive focus on the top scorers. In the case of pain point voting, the result was a prioritized list of what each breakout group deemed to be its largest current state challenges.

This result was used as input for the next cycle of ideation and prioritization, in which opportunities for each of the top pain points were subsequently generated and prioritized, resulting in a list of the top opportunities mapped to each of the top pain points. Similarly, the top opportunities were then used as input to identify the limitations of current state AM technology.

Collectively, these participant-generated lists formed a detailed picture of the current state across CF operations, AM technology capability, and future state. For each opportunity, participants generated actionable and measurable goal statements within their breakout groups. Different combinations of processes and materials were also mapped to specific opportunities to achieve the goal at hand.

3.1.4.2 Functional Analysis Workshop

Functional Analysis Workshops were structured to expand the project definitions and activities sourced from the Visioning Workshop synthesis into detailed and prioritized execution plans. Each of the resulting plans outlines the schedule for implementation, overall cost, key metrics, and deliverables.

Execution plans were constructed in breakout groups. The breakout groups were tailored in advance to pull subject matter experts of focused expertise together across the CF and AM ecosystems. Each breakout group was provided with 2-3 carefully selected goal statements to maximize the application of each group's collective specialized knowledge. Breakout groups were guided through a series of exercises designed to define the key elements of each project. Discussions were facilitated to specify the following attributes:

1. **Impact Statements**: Develop a statement for each project that captures the value enabled by delivering the project
2. **Activity Validation**: Modify, add, and validate the activities to realize project aspirations
3. **Initiative Duration & Sequence**: Create a step-by-step timeline of when each initiative should take place
4. **ROM Costing & Success Measures**: Estimate how much each project will cost and how to track and measure success
5. **Project Prioritization**: Track impact and effort to prioritize projects moving forward

Data was subsequently gathered to identify the preliminary prioritization unique to the casting and forging communities. Plans were grouped based on casting/forging applicability and were provided to the larger set of participants for voting on along two dimensions:

- **Impact:** How much impact the project will have on reducing lead times for casting and forging components to improve wartime readiness, regardless of difficulty
- **Effort:** The relative difficulty of what it will take to accomplish project scope, considering current technology maturity, workforce capability, and ease of execution

The data collected along these two dimensions was plotted onto a two-dimensional matrix, with preliminary priority quantitatively determined by ranking the weighted sums. This structure was adopted to enable a common comparison across projects while simultaneously grouping projects of similar 'profile' (e.g., shorter-term and well-defined as opposed to loner-term with high uncertainty).

Key materials and processes for each project were also identified and ranked by workshop participants. Alongside project priority data, a layered synthesis was constructed to identify top-priority projects and key materials/processes within them. Additional effort was undertaken to supplement the workshop dataset with historical sourcing data for cast and forged components. This analysis is discussed in Section 4.3.

Detailed project and prioritization findings were reported individually to ensure technical nuance was captured. The workshop dataset and historical sourcing data were subsequently used in a combined synthesis to generate preliminary roadmaps, the structure of which is discussed in Section 5. Collectively, these materials were used as input for the Validation phase.

The results from the workshop were synthesized using the same process outlined in 3.1.4 to build the project plans. Specifically, data for each project and across workshops were combined, coded, and compared. Common activities across projects were identified to standardize naming, duration, and associated output.

3.1.4.3 Validation Workshop

The Validation Workshop convened a subset of the Government Advisors to thoroughly review all roadmap materials. Specifically, the workshop served to drive a direct path forward to the finalized roadmap by addressing three primary objectives:

- **Align** on roadmap structure and organization
- **Approve** or adjust findings from workshops at the project level
- **Identify** gaps and potential synergies across projects

Review of the roadmap structure focused on the sequence, duration, and delivery schedule for the complete set of projects. The organization of each project into common groups (swim lanes) was reviewed alongside the method and definition for each swim lane. This process is discussed in detail in Section 5.

Each project and its attributes (e.g., cost, priority) were reviewed individually with a focus on enabling detailed and deeper discussions. To do so, workshop materials were provided to all participants one week in advance for markup. The received set of feedback was subsequently cross-referenced, highlighting contrasting feedback and suggested adjustments. These areas served as prompts within each project's review to align on necessary updates as a group.

Feedback captured during the validation workshop was addressed in a follow-up working session where each project was refined. Additional detailed views were built to highlight the interdependencies across the projects, and the final strategic roadmap was constructed. A final review with project sponsors was held to confirm that the updates sufficiently addressed the feedback captured in the Validation Workshop.

4 Insights

4.1 Literature Review and Interviews

The combined synthesis of literature review and interview data highlighted opportunities to better align AM development to the immediate needs of the casting and forging ecosystems. These opportunities are particularly prevalent upstream of and as an input to casting and forging processes in contrast to focusing on direct part replacement. Examples include printed ceramic shells for investment casting and printed preforms for closed-die forging.

This is supported by individual findings within each dataset indicating:

- Academic research is largely focused on material optimization of metal components
- Qualifying printed replacement parts and process changes are a significant challenge
- Applying AM to tooling, rather than the part itself, can drive flexibility and cost savings

4.1.1 Literature Review

The 102 academic papers highlighted two groups of technical approaches, delineated by whether the study sought to produce an end part or an input to established processes. With most studies addressing broad topics of direct part replacement and with limited data assessing development against the requirements of established material specifications, three primary opportunities emerged as input to interviews and workshops:

- Drive focused development applying AM upstream of primary CF steps
- Enable a broadened material portfolio for applying AM solutions to CF operations
- Baseline current AM solutions against DoD-unique cast and forged product requirements

Figure 7 depicts the distribution of coded topics, highlighting the difference in how frequently each approach was adopted. Studies producing direct replacement parts comprise the topics of material performance, hybrid manufacturing, and part qualification. This collectively represents 52% of the recorded topics, compared to the 16% of casting and forging augmentation topics.

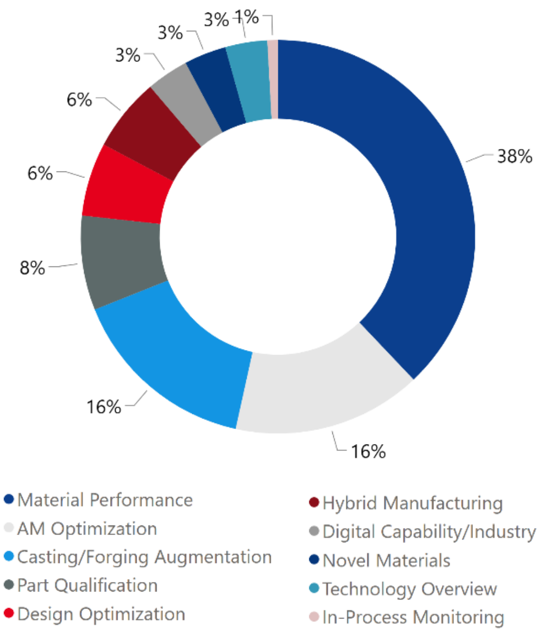


Figure 7: Literature Review Topic Distribution

A significant difference was also prevalent in each group's material systems. Direct part replacement is heavily focused on non-ferrous alloys, which account for 66% of the studied material systems within the group. A small number of alloys are prevalent, with Ti6Al4V and IN718 collectively accounting for 48% of these non-ferrous alloy systems, as shown in Figure 8. A similar prevalence was present within ferrous metals for direct part replacement, with 316L individually accounting for 33%. For legacy DoD platforms, this suggested development opportunity to enable a broader portfolio of AM materials.

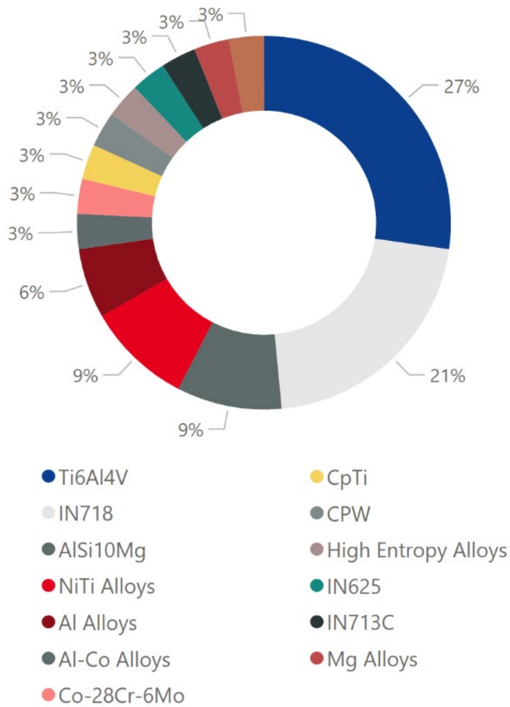


Figure 8: Non-Ferrous Alloys in End-Part Replacement Studies

In contrast, studies addressing upstream CF augmentation focused primarily on polymers and waxes, which accounted for 59% of materials studied within the topic area. Metal materials studied within this group represented an additional 35%, which included printed components in H10 and Ti6Al4V for printed tooling and printed preform study, respectively. Figure 9 shows the breakdown of material systems studied within the casting and forging augmentation topic group. The findings similarly posed a potential opportunity to expand material portfolios for upstream-specific solutions, such as printed tooling, waxes, and ceramic shells.

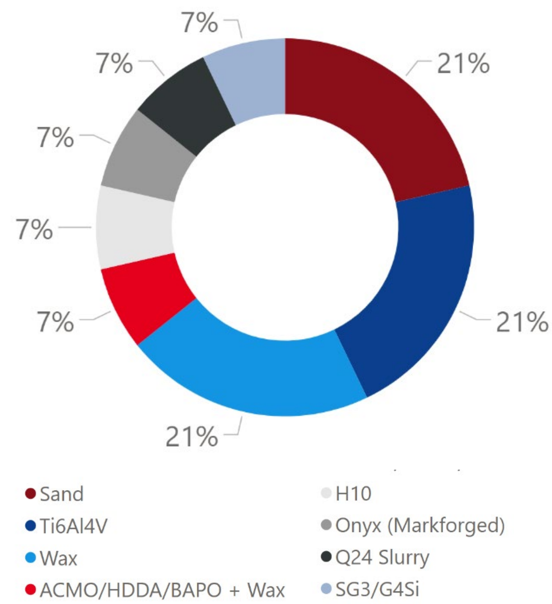


Figure 9: Materials in Casting and Forging Augmentation Studies

4.1.2 Interviews

Interviews with subject matter experts provided critical insight into where and how potential AM solutions could be deployed to realize a meaningful impact in production. Three key areas were identified from the interviews and subsequent data synthesis:

- Qualification and certification processes
- Legacy part specification definition
- Management and manufacture of low-volume tooling

These collectively pose significant and complementary challenges that lead to no-bids, particularly in the case of low volume and legacy system orders with little opportunity to amortize upfront costs. Additionally, navigating these challenges significantly contributes to long lead times for parts.

Industry experts indicated that the qualification process can be cost and time-prohibitive in many cases through production and subsequent acceptance. The contributing factors surrounding qualification combine technical and non-technical challenges; see Section 7.2 for discussion on the non-technical aspect. The technical challenges are primarily focused on the part specifications. Specifications can be confusing or incomplete, impacting the ability to fully understand the properties and testing required to meet the contract. This is compounded for legacy components that are defined on paper or lack the 3D models to retool. In one example, a participant commented that traditional tooling can have a lead time of 20 weeks, and model generation adds to this time.

Tooling individually emerged as a key to augmenting CF with AM, representing over 50% of the opportunity data collected through interviews. The ability to additively manufacture tooling has the potential to significantly impact industry, see Figure 10. The AM tooling opportunities include printing molds, cores, patterns, dies, and preforms, along with the capability for advanced tooling design and tool repair.

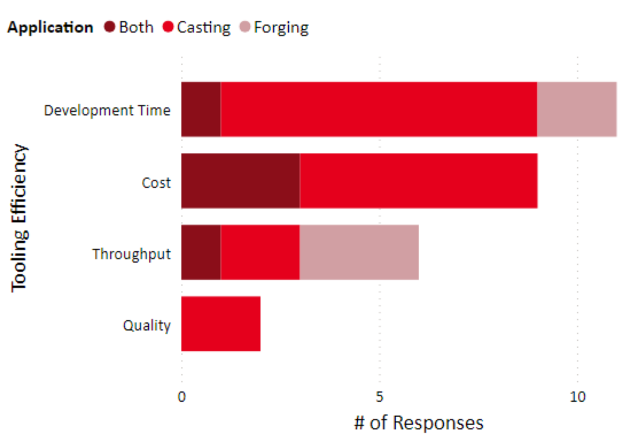


Figure 10: Tooling Efficiencies Discussed During Interviews

An interviewee discussed how additively manufactured sand molds could reduce the time to first part from over a year for traditional tooling to as low as three months due to the ability to iterate through mold designs quickly. The tooling efficiencies can be cumulative since the reduction in cost and time eases the burden of tool replacement as tolerances expand, positively impacting part-to-part quality.

> *"[It takes] 3-6 months to get a product to the customer for qualification with 3D printing compared to 12-18 months for traditional tooling"*

Utilizing AM for directly printing government parts amplifies the qualification concerns present in traditional manufacturing due to the uncertainty in mechanical properties. Since AM tooling is a change to the process rather than the part, these qualification concerns are mitigated.

> *"The least change from the original part the better. If we can work on printing the tools, we can address the risk averseness [of the DoD] and retesting and revalidation."*

In addition to low-volume and legacy production benefits, AM tooling will be a powerful capability for new, complex designs. Manufacturing capabilities will always limit part design, but AM expands those capabilities. Core consolidation is an example of these benefits with AM tooling. As part designs advance, AM will become critical for manufacturability. Increasing the knowledge base on design for AM (DfAM) is vital to the industry.

> *"[We are at an] inflection point with part design today, where engineers are challenging the boundaries of traditional castings where AM is the only solution"*

Digital solutions are necessary to fully utilize AM in the casting and forging industries. The digital solution opportunity space includes computer-aided design (CAD) conversion and simulation. CAD conversion addresses the pain point surrounding drawings for legacy components, and simulation efforts strive to improve first article acceptance by reducing uncertainty within AM.

The synthesized output from these interviews served as the input for the workshops. The pain points, opportunities, and AM shortcomings that resonated the most with the interview participants were reviewed with the advisory board and chosen to be used as material to ignite thought during the workshop exercises.

4.2 Workshops

4.2.1 Visioning Workshop

The Visioning Workshops convened 95 attendees representing 75 organizations across industry and government. This broad and diverse group generated 54 individual goal statements, which set the direction for future project definition. Five key themes emerged across casting and forging:

- **AM for Tooling:** AM for tooling is the most feasible solution, as the final part is not being altered, easing qualification requirements while speeding up the time to get tooling and lowering the cost
- **Confidence in AM:** Due to underdeveloped standards and limited characterization of the material properties, there is a general lack of confidence in the repeatability of AM compared to CF processes
- **Modeling and Simulation:** The industrial base desires to improve modeling and simulation tools to improve decision-making, increase confidence in part performance, and speed up the qualification process
- **Assisted 3D Model Creation:** The industrial base desires improved tools to assist with converting 2D drawings to 3D CAD models when the drawing exists and tools for reverse engineering when it does not
- **Workforce Enablement:** Workforce enablement was cited as a current pain point with CF operations and as a gap in implementing AM solutions

While these themes are shared across CF ecosystems, unique insights and prioritization of pain points, opportunities, and AM shortcomings exist within each.

4.2.1.1 Casting

The casting-specific data reflected the importance of addressing challenges within and surrounding the casting process. Bottlenecks exist across the value chain and are technological, procedural, and workforce-related. Leveraging the flexibility of AM at these focused points presented opportunities to reduce lead times and make low-volume orders more economically viable.

Furthermore, the use of AM in casting applications has been demonstrated and is currently used in facilities where dedicated investment has been made to develop internal capabilities. The casting-specific goal statements reflect the opportunity to stabilize and scale these models across casting processes and facilities through tools to select and efficiently implement AM technologies.

A sample of goal statements is provided below:

- Develop design guidelines to educate designers on DfAM and economic cost modeling for comparison processes
- Develop more mature ceramic printing processes to enable widespread use and adoption by industry
- Automated/AI conversion of 2D drawings to 3D CAD with metadata and specifications
- Minimize tooling on hand by using low-cost printed patterns to reduce bidding risk on low volumes
- Improve the surface finish of sand molds to match conventionally made molds
- Reduce scrap, aid cost, and improve properties/performance by using conformal cooling to reduce casting defects from various sources

The pain points the goals were written to address span the process flow, including upstream 3D model creation, reduction of tooling and its management, and downstream post-processing. Four of the top seven pain points could not be addressed with a technological solution and were filtered out for subsequent opportunity identification. The top seven pain points are listed in Table 5.

Table 5: Top Casting Pain Points

1	The qualification process can be challenging, lengthy, and costly
2	The wealth of knowledge in the industrial base is declining
3	The specifications for legacy parts are not always clearly defined and are open to interpretation
4	Tooling can be difficult to manage
5	Needing to convert 2D drawings to 3D CAD models for legacy components
6	Bidding on low volumes is too risky
7	Machining and grinding bottlenecks extend lead times

Opportunity rankings similarly reflected the potential of applying AM upstream of casting and across the different casting specializations. Three of the top seven opportunities seek to remove conventional tooling, with the top two opportunities highlighting the impact of tools that remove uncertainty from design and technology selection. Direct part replacement was ranked as the seventh highest opportunity as it carries the challenges of qualification (the top pain point). The top seven opportunities are detailed in Table 6.

Table 6: Top Casting Opportunities

1	Modeling and simulation tools to improve the design process
2	Develop tools/guides to assist with technology selection and design
3	Printing sand molds and cores
4	Reverse engineering tools to shorten design lead times
5	Printing ceramic molds and cores
6	Printing patterns
7	Use AM to produce a traditionally cast part

The three highest-ranked AM gaps for casting were focused on education and best practices within AM. As these are not traditional technology development shortcomings, these findings underscore the importance of dedicated strategic communications efforts to ensure scaled adoption through knowledge sharing across casting specializations and facilities.

4.2.1.2 Forging

The data gathered from forging breakouts outlines the ability of AM to support flexibility and productivity across the value chain. To drive reduced lead times for forgings, having raw material on hand is crucial, alongside minimizing press downtimes and accelerating die manufacture and repair.

The forging-specific goal statements generated set the direction for how AM can leverage printed material as an input to the forging process, keep critical equipment running with short-term components, and extend the life of components and dies. A sample of the statements is provided below:

- Develop industry standards and specifications for using AM tooling repair processes
- Collaborate with industry partners to qualify factors where AM preforms have value
- Characterize materials and the interface for using AM to add material to forgings
- Develop reliable and cost-effective AM for forging dies to improve cost efficiency, reduce lead times, and save costs

The top-ranked pain points within forging breakouts that drove these statements highlighted challenges across technology, procedure, and workforce. Four of the seven highest-ranked pain points could not be addressed by technological solutions and were filtered out for subsequent opportunity identification. The remaining pain points highlight the challenges upstream of the forging process in sourcing raw materials (a problem that scales with component size) and 3D model creation from legacy and paper-based engineering drawings. Table 7 details the list of the top seven forging pain points.

Table 7: Top Forging Pain Points

1	The wealth of knowledge in the industrial base is declining
2	Needing to convert 2D drawings to 3D CAD models for legacy components
3	Workforce shortage and knowledge gaps in the education system
4	The qualification process can be challenging, lengthy, and costly
5	Tooling can be difficult to manage
6	Raw material sourcing lead time from approved suppliers
7	Workforce development and staffing

Table 8: Top Forging Opportunities

1	Modeling and simulation tools to improve the design process
2	Use AM for tool repair and keep manufacturing “in the fight”
3	Use AM pre-forms (and AM-assisted cast pre-forms) to eliminate upstream processes
4	Use AM to add features or high-wear layers to forgings to enhance performance
5	Use cold spray and DED to repair forged parts
6	AM prototypes to speed up development activities and/or fixturing setups
7	Printing dies

The ranked opportunities similarly emphasized the benefit of flexible and optimized input to the forging process. This was evident through the top-ranked opportunity of modeling and simulation, which poses a significant benefit if the number of forging steps can be reduced through simulation-based solutions. The capability to repair and add functional surfaces to forged components and forging dies can relieve stresses from the supply chain by allocating critical raw materials where necessary, leveraging AM material forms to print pre-forms of varying shapes and sizes. Table 8 details the complete list of ranked forging opportunities.

Like casting, the three highest-ranked AM gaps for forging focused on the education and best practices within AM. With declining workforce knowledge highlighted as the top forging pain point, this result further underscores the importance of driving AM knowledge dissemination across industries.

4.2.2 Functional Analysis Workshop

The Functional Analysis Workshops convened 86 attendees representing 60 different organizations. The group was provided with initial projects and their comprising activities and collectively built execution plans for 14 projects while contributing 142 new activities within the plans.

The resulting set of projects established that developing common capabilities across industries and technical domains is necessary to implement AM at scale. These capabilities extend beyond individual printing technologies and emphasize the need for structured deployment, training, and guidance for adopting AM in CF production settings. Furthermore, the digital-physical nature of AM necessitates that digital infrastructure be developed to accelerate deployment through scaled usage of 3D models and simulation tools.

The key themes underlying these capabilities are:

- **Path to Print:** Playbooks to deploy AM technology for patterns, molds, dies, and repairs
- **Shared Understanding:** Common guidance on when to print, capable vendors, and how to measure performance
- **Integrated Tools**: AM material property predictions as input to broadly used software
- **Digital Foundation:** Common technical data packages (TDP) structure with processes to build digital stockpiles
- **Sustainable Training:** Accessible AM resources contained and grown within Casting and Forging communities

While the themes apply to both casting and forging domains, the casting and forging ecosystems prioritized their projects differently according to their unique needs.

4.2.2.1 Casting

The top casting priorities from the workshop focused on delivering flexibility through reduced reliance on tooling and agility through digital model creation and simulation. Combined with the material data gathered, the top priorities addressed challenges with sourcing steel and aluminum components across sand, investment, and die casting, with the digitally focused projects applying to all.

The priorities exist across a spectrum of technology maturity. Their execution plans emphasize the need not only to develop but also to deploy AM capabilities and provide structured guidance on when and how to use them. The top priority is deploying demonstrated sand casting capabilities across new facilities and components. The second highest priority for printing ceramics in investment casting is still largely in development and constrains build volume in its current state. See Table 9 for the top five projects.

Table 9: Priority Ranking for Casting Projects

1	Disseminate leading practices and promote the adoption of 3D printed sand molds/cores
2	Mature ceramic AM technology to enable rapid pours into integrated shells and cores
3	Develop and disseminate performance-enhancing tools for implementing AM conformal cooling
4	Accelerate the creation of TDPs and CAD models for legacy components
5	Develop digital infrastructure and data models for use in DoD process flows

For sand and investment casting, using AM to remove the need for hard tooling significantly benefits non-recurring engineering (NRE) costs and lead times. Similarly, creating and disseminating tools to implement conformally cooled die casting molds can remove the need for specialized labor and drive costs out of improving cycle time and die life.

The acceleration of 3D/CAD model creation is critical to enabling each of these technologies to be implemented. In addition to posing a current challenge, 3D models are critical to additively manufacturing sand molds and ceramic shells. The digitally focused priorities recognized this need from both a current and future state perspective. Likewise, creating a common structure to store and communicate this information is necessary to define inputs to the casting process, as well as support longer-term efforts that capture process data and seek to implement predictive solutions.

The priorities were derived from an impact and effort scoring exercise. The impact and effort scores reflect the distribution of technology maturity across projects, with earlier phase technologies like printed ceramics ranked higher on effort than those that are more mature, like sand printing. The prioritization of projects was realized by a 75% and 25% weighting of impact and effort, respectively, based on feedback from the Advisory Board.

The material data gathered reflected a consistent opportunity for aluminum castings across projects and a tendency to prioritize ferrous alloys over non-ferrous in alignment with the characteristics of many legacy platforms.

Figure 11 shows the distribution of impact and effort scoring for casting projects, the resulting project priorities (shown top to bottom), and their associated material priorities (color-coded).

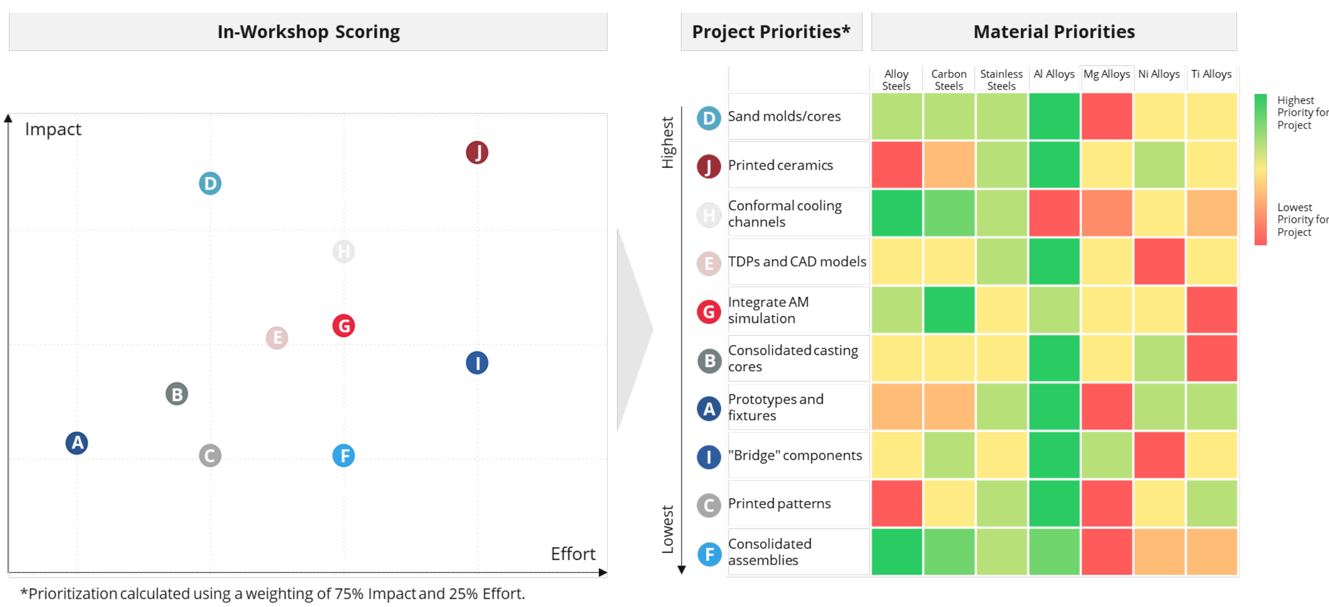


Figure 11: Impact/Effort Scoring and Prioritization for Casting Projects

The synthesis of project and material priorities, combined with the identification of common themes across projects, illuminated opportunities to consolidate or split certain projects. Technological focus area and maturity were the key drivers used to form projects for the final roadmap structure; see Appendix I for details.

4.2.2.2 Forging

The prioritized forging projects from the workshop desired to extend the lifetime of tooling and components, driving productivity through flexible repair and material input strategies. Combined with the material data gathered, the top priorities seek to improve the responsiveness and economic viability of low-volume steel forgings.

The use of AM in forging is less prevalent than in casting, as it is more difficult to demonstrate how and when printed input material can be processed to meet forged component performance requirements. Conversely, reliance on forging equipment and tooling availability demonstrated unique opportunities to provide fast and flexible solutions that keep productivity high with short-term repair options.

The forging project with the highest priority in particular leverages AM to keep presses running and maintain operational status with intentionally short-term AM components. The top five prioritized projects are forging are detailed in Table 10.

Table 10: Priority Ranking for Forging Projects

1	Establish a scalable AM "bridge" component sourcing model to keep critical production equipment running
2	Mature and promote methods to add functional surfaces and complex geometric features to forgings
3	Develop and disseminate leading DED, friction stir + thermal, and cold spray practices to promote the adoption of planned and unplanned tooling repair and modification application
4	Pilot the industrialization of AM preforms to expedite the forging process for low-volume components
5	Pilot the industrialization of AM dies to expedite the forging process for low-volume components

Utilizing AM to add features to a forged part aims to reduce material and downstream operations required to arrive at a final net shape. This hybrid method poses benefits across the value chain, including increasing throughput, reducing lead time, and opening capacity for downstream machining. Another benefit of hybrid AM and forging is the ability to add wear layers to extend the life of a part and reduce long-term demand. Projects focusing on this area were scored highly on impact as a result.

While repair options are in place today, many require highly specialized labor and significant post-processing to restore the form and finish of the die. AM's flexibility offers cost advantages to treat repair similarly to low-volume production, handling the aspects of customization with technological capability and enabling specialized labor to work on other complex tasks and decisions. Execution plans built in this area focus on providing structured guidance on when and how to deploy these solutions.

Where repair or feature addition is not viable, enabling flexible material input through printed preforms and printed dies provides a solution for low volumes. Projects in this area focus on industrialization and proving performance by defining a pathway to connect existing processes.

The material data gathered across the forging projects reflects the need to enable these solutions for ferrous alloys. This includes projects focused on dies, which typically use specialized steels.

Figure 12 shows the distribution of impact and effort scoring for forging projects, along with the resulting project priorities (shown top to bottom) and their associated material priorities (color-coded).

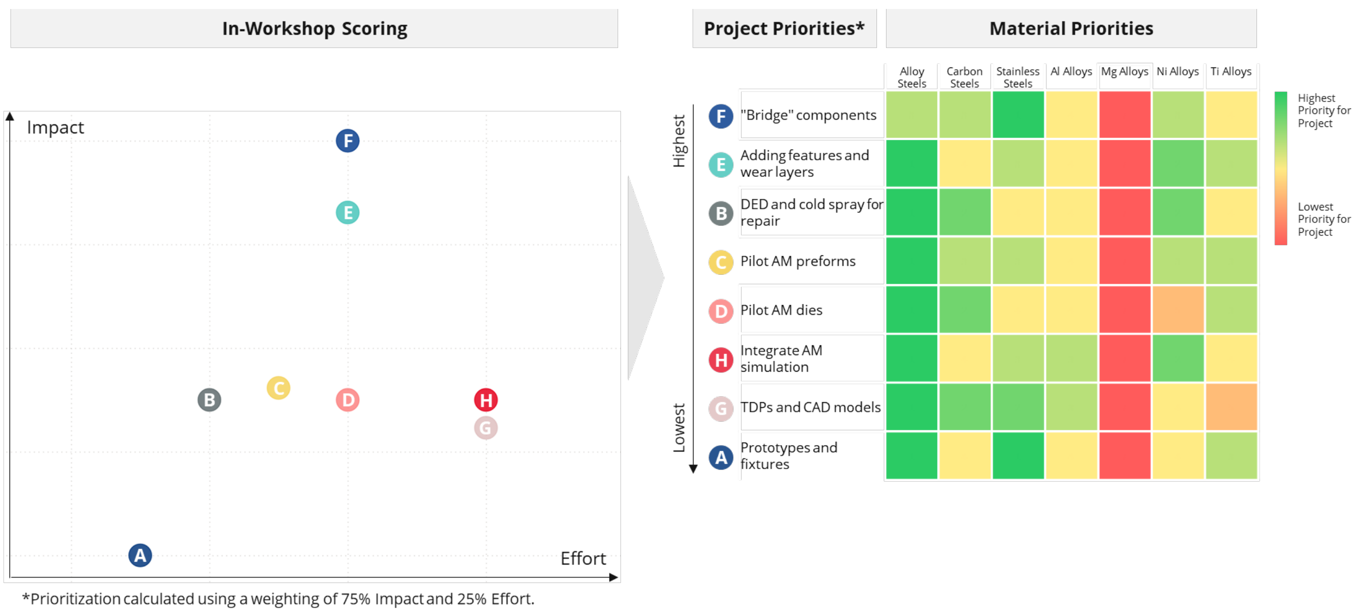


Figure 12: Impact/Effort Scoring and Prioritization for Forging Projects

The synthesis of project and material priorities, combined with the identification of common themes across projects, identified opportunities to consolidate or split certain projects. Technological focus area and maturity were the key drivers used to form projects for the final roadmap structure; see Appendix I for details.

4.2.3 Validation Workshop

The Validation Workshop convened a focused group of 10 key stakeholders representing a broad set of government and DoD perspectives. A preliminary roadmap of 17 detailed project plans was reviewed using synthesized output from the Functional Analysis Workshop.

From the review of the preliminary roadmap, two key takeaways emerged from the session:

- Projects should be sequenced to maximize parallel efforts and highlight dependencies, creating a timebound view

- Casting and forging-specific projects should be collected into a consolidated roadmap for the purposes of program management

The detailed and technical review of the projects, along with their associated execution plans, costs, and prioritizations, yielded three key takeaways:

- Execution plans should be structured to facilitate program management with structured sets of development across materials/components
- Execution plans should be structured to emphasize incremental delivery throughout a project's duration, highlighting where value delivery occurs
- Results of each project should be emphasized in terms of quantifiable numbers of materials and components studied/assessed

Modifications were made to all projects and their organization within the roadmap. The changes adopted a 'line of effort' structure to address the program-management-related needs and to structure packages of work along the lines of individual materials/components of focus. This structure is discussed in detail within Section 5.

The restructured materials were presented to project sponsors in a dedicated follow-up session, which revisited each project in detail alongside the modified roadmap. An example project breakdown from the session is depicted in Figure 13.

Feedback gathered during both validation sessions led to the creation of the structured roadmap and finalization of individual projects. Examples of the finalized materials were presented to the Advisory Board for final validation. The materials collectively covered all levels of the roadmap structure discussed within Section 5.

4.3 Order History Analysis

The material and process data gathered in workshops were supplemented by an additional analysis of DoD order data. Collectively, the two analyses provide a comprehensive view of which materials and processes should be prioritized to effectively

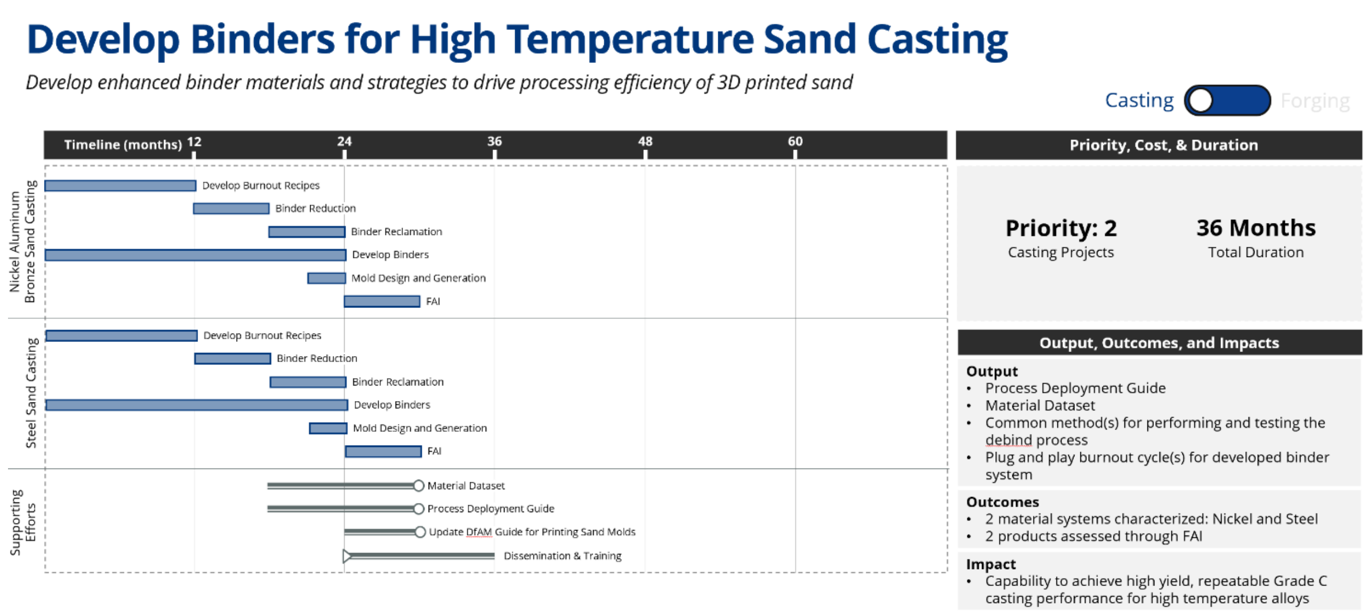


Figure 13: Sample Project Breakdown from Validation

support and improve warfighter readiness. Insights informed the assignment of materials within the projects' lines of effort.

There are multiple aspects of readiness, which can be equally affected by one missing component as one hundred. Furthermore, the components required to immediately support readiness dynamically change with time and emerging needs. The needs of individual platforms are not captured without dedicated datasets relating components to the platforms on which they are used.

The synthesis covers a two-year period, assessing backorder quantities and lead times related to individual casting and forging processes and materials. Across these four fields, two matrixed views were created to drive insight.

There are three primary takeaways from the analysis:

- Across casting and forging materials, steel and aluminum have the largest total backorder quantities
- Investment casting and closed die forging have the longest average lead times for casting and forging processes, respectively
- Order history data reflects similar priorities as indicated by workshop data

4.3.1 Material and Process Matrices

Matrixed views were created to identify combinations of materials and processes that pose the greatest challenges along the dimensions of average lead time and total backorder quantity. Unfulfilled orders were the primary data points analyzed, with the lead time representing the difference between the scheduled delivery date and the order date.

The average lead time for each process-material combination was analyzed to identify which materials need to be prioritized for a given process (see Figure 14). The materials with longer lead times were inferred to be a higher priority, as indicated by cells highlighted in red. Materials with shorter lead times are characterized by cells that are highlighted green. Material-process combinations within the matrix without unfulfilled orders are left blank for simplicity. A similar analysis was conducted using total backorder quantity as a proxy for priority (see Figure 15).

Measuring average lead time provides a measure of how consistently certain materials and processes are unfulfilled and a relative prioritization based on how long they have been unfulfilled. Specific priorities from the data can be identified by considering sets of materials, sets of processes, or individual combinations.

While they do not have the highest average lead time, steel and aluminum consistently show unfulfilled orders across processes. Cobalt and titanium demonstrate higher lead times within relatively fewer combinations with unfulfilled orders. Magnesium contains the highest individual combinations and highlights a focused priority in sand casting.

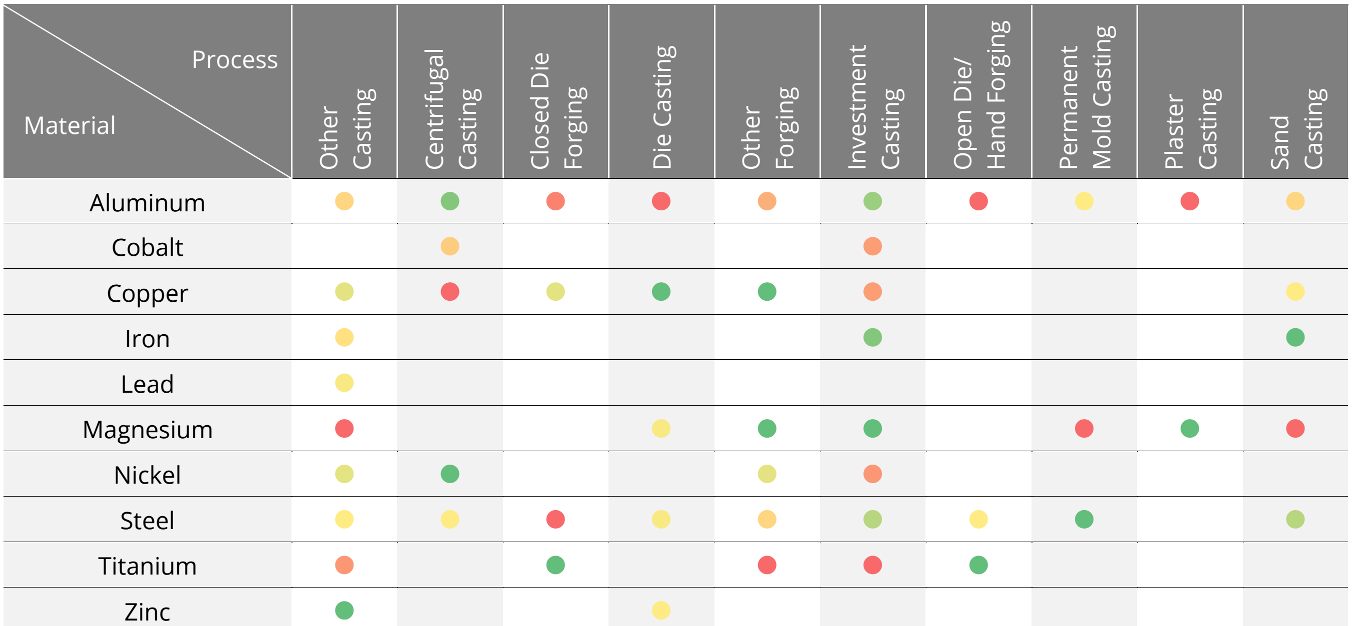


Figure 14: Material and Process Matrix: Average Lead Time of Unfulfilled Orders

Measuring total backorder quantity provides a measure of the relative magnitude of individual unfulfilled orders, which illuminates individual orders with high backorder quantities. Similar to average lead times, the steel and aluminum consistently show unfulfilled orders across materials. Investment casting and die casting present the highest total quantities across processes. For individual material-process combinations within die casting, it was observed that aluminum had the highest backorder total, whereas titanium was the highest for closed-die forgings.

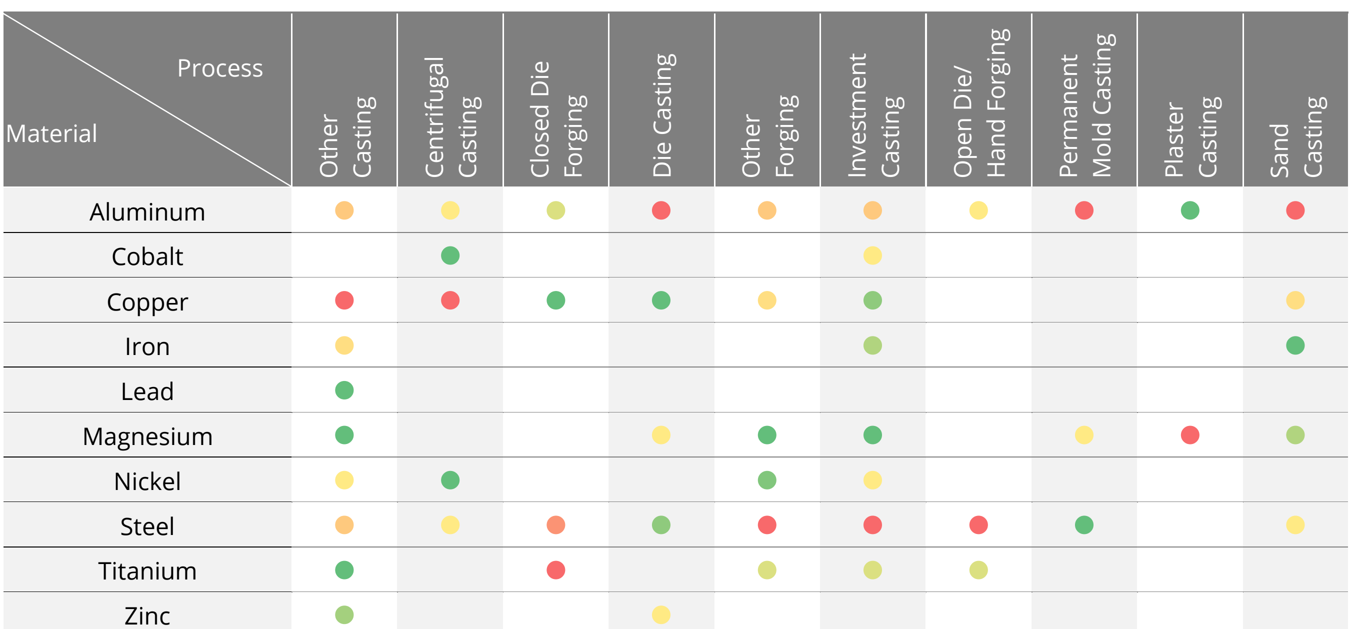


Figure 15: Material and Process Matrix: Total Number of Parts Backordered

4.3.2 Lead Time and Backorder Distributions

To understand the combined influence of lead time and backorder quantity on material-process combination priorities, the two attributes were plotted as two dimensions on an XY-scatterplot, as shown in Figure 16. The total lead time and backorder quantities demonstrate a cumulative effect, with steel and aluminum materials standing out again across casting and forging.

Figure 16 also draws the reader's attention to copper casting. It should be noted that the dataset does not provide further specificity into a specific casting process or a specific alloy containing copper, such as nickel aluminum bronze. The industrial base will benefit from further studies to narrow in on priorities for process-material combinations.

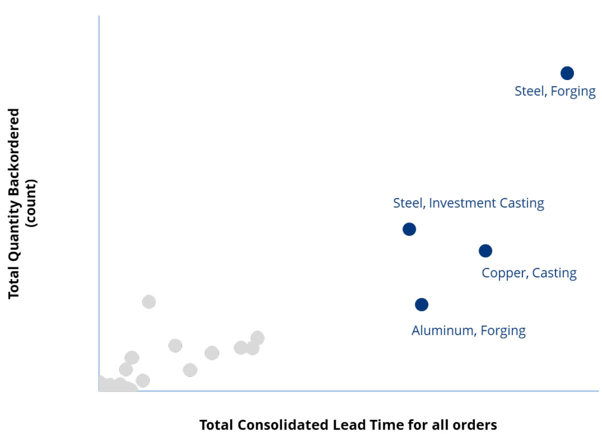


Figure 16: Material-Process Scatterplot: of Total Backorder Quantity and Lead Time

The average lead time and backorder quantities in Figure 17 demonstrate a normalized effect. Cobalt and nickel investment casting, along with magnesium casting, are highlighted with both higher average lead times and backorder quantities. The combination of low lead times and high backorder quantities for zinc castings poses the potential for mitigating efforts to ensure lead times stay down.

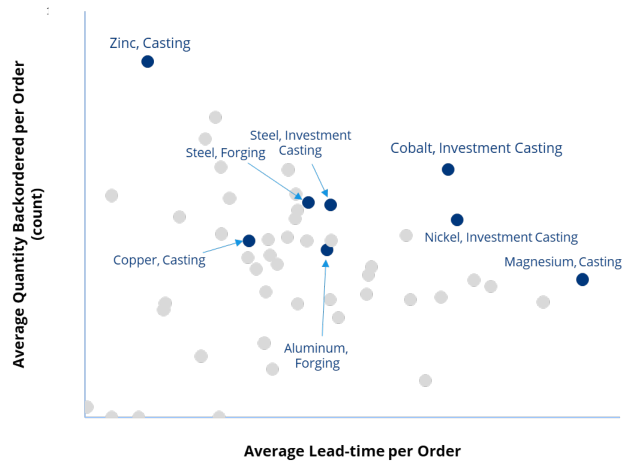


Figure 17: Material-Process Scatterplot: Average Backorder Quantity and Lead Time

Notably, the material-process combinations identified by the cumulative comparison distinguish themselves slightly differently than the average comparison. This indicates that it is likely that the totals in Figure 16 are more driven by a smaller set of outliers with higher lead times and backorder quantities. From a volume perspective, steel, aluminum, and Copper are presented as priorities; however, both data sets should be considered in line with the multiple aspects of readiness.

The findings and primary material prioritizations align with the synthesis of workshop data, emphasizing the importance of steel and aluminum component sourcing across CF processes. Order data analysis served as a complementary set of information to select materials within the projects' lines of effort, in tandem with workshop data and Advisory Board input.

5 Roadmap Structure

The roadmap is structured as a hierarchical system that defines the strategic path forward and facilitates the management of the overall program at all levels. The roadmap consists of casting and forging specific projects consolidated into a collective view, specifying each ecosystem's efforts while highlighting joint efforts that apply to both. The next level, swim lanes, organizes projects that aim to achieve similar outcomes and are delineated along the lines of technology maturity and the digital-physical nature of AM. Finally, the project level details execution plans and outcomes.

The sequence and duration of the roadmap reflect a timebound execution that maximizes parallel efforts to accelerate return on investment and focuses on delivering incremental value through efforts to reproduce outcomes, document findings, and disseminate knowledge. In a cost-constrained scenario, the roadmap's structure enables individual projects to be selectively funded, effectively shifting the start date based on budgetary restrictions. Dependencies across projects have been highlighted, and each project is assigned a recommended priority for informed decision-making in these scenarios.

5.1 Roadmap Level

The highest level of the roadmap structure depicts the multi-year view of all projects, summarizing their attributes and impacts of delivery. It provides the framework for down-selecting projects and their activities for funding, organizing the overall project by applicable ecosystem (casting/forging) and area of focus (swim lane). Within each swim lane, casting and forging-specific projects are grouped and subsequently arranged from top to bottom to reflect relative priority.

The capability deployment icon denotes when a project transitions from deployment-oriented efforts to driving scale and adoption. Capability deployment also designates the point at which each project initiates delivery of incremental value. While the details of these deployments differ across projects, they seek to reproduce key outcomes and stress-test development across additional facilities and components.

Within the Supporting Efforts swim lane, common and documentation-related efforts are collected into continuous projects. The timing of these projects is aligned across the roadmap; the start and end dates of Supporting Efforts projects represent the start of the first and the completion of the last documentation, respectively.

5.2 Swim Lane Level

This roadmap level presents a deeper look into each swim lane and the projects that comprise it on the same timescale as the roadmap level. Like the Roadmap Level, the Swim Lane Level depicts the multi-year view of projects within the Swim Lane. It also provides each project's total duration, time to first deployment, and summarized impact statement.

Each project at the swim lane level is broken down into lines of effort. The lines of effort group individual activities within a project that should be performed together. This grouping differentiates between development and scaling-related work, enabling a similar function for program management to selectively fund each line of effort. Along these lines, individual lines of effort have been built into each project for material-unique sets of development. This structure drives agility for the roadmap to flexibly respond to DoD needs as material priorities may rapidly change over the coming years. At this level, which level of effort is triggering capability deployment is visible, along with when deliverables are expected to be submitted. The dependencies highlighted at the roadmap level are also maintained and connected to individual lines of effort.

5.2.1 Swimlane Definitions

The swim lanes were procedurally defined by synthesizing data from the Functional Analysis Workshops. Execution plans defined by workshop participants were matrixed and compared to identify common outcomes and activities. The commonality of outcomes drove the grouping of the projects, resulting in groupings aligned to varying levels of technology maturity and based on digital versus physical nature. Upon recognizing common initiatives across projects, a dedicated swim lane was created to focus on centralizing documentation-related activities instead of being housed within each individual project. This centralized structure promotes streamlining of execution and delivery through continuous projects while encouraging collaboration and knowledge sharing across projects.

The resulting swim lanes are described below:

- **Scale Current State**: This group of projects aims to disseminate established technology beyond siloed pockets of expertise. The capabilities that these projects promote tend to be more mature compared to the Prove Production Capability Swim Lane
- **Prove Production Capability**: This group of projects seeks to mature demonstrated and emerging technology to predictably meet production needs. The capabilities that these projects promote tend to be less mature compared to the Scale Current State Swim Lane
- **Build Digital Foundation**: These projects will help establish an infrastructure for components and simulation models to drive agility and accelerated design cycles. As the name describes, these projects are foundational for the future deployment of advanced manufacturing technologies across DIB and OIB
- **Supporting Efforts**: These projects centralize common activities across the projects in other swim lanes to drive the adoption of the developed capabilities. These projects standardize documentation, drive efficient delivery, and strive to build awareness and competency across the DIB and OIB

5.3 Project Level

Projects are detailed execution plans that drive individual activities to a specific application domain and outcome. In addition to designating the ecosystem and swim lane, the project level provides a structured and comprehensive breakdown that details priority, schedule, and results (output, outcomes, and impact).

5.3.1 Priority

Projects are prioritized relative to one another and within groups of casting-unique, forging-unique, and shared projects. Data from the workshops has been integrated to arrive at the individual rankings using a combined measure of the expected impact of successful delivery and the effort necessary to execute the activities.

The numerical ranking indicated at the project level is reflected upwards at the swim lane and roadmap levels by the arrangement of projects, generally following an ordering of higher to lower priorities moving from top to bottom.

5.3.2 Schedule

Project-level schedules detail the specific activities to be performed within the individual lines of effort. Like other roadmap levels, this schedule represents a timebound execution plan that maximizes parallel work to accelerate capability deployment. This structure enables a clear visualization of dependencies across project activities. While each project is unique, dependencies and sequential activities generally fall into one of three categories: development, testing (e.g., first article inspection [FAI]), or deployment (e.g., transferability pilot).

Supporting Efforts activities are identified within the schedule and visually indicated with color coding. Activities not housed within a line of effort represent key input to multiple lines of effort or are separate exploratory efforts with no dependencies on other lines of effort.

5.3.3 Output, Outcomes, and Impact

The delivery attributes for each project are detailed within dedicated sections for output, outcomes, and impact. These attributes collectively define what that project will deliver, tangible and otherwise:

- **Output**: Outputs include the direct and tangible deliverables and documentation of the project that serve as evidence of the capability being developed and artifacts to support its deployment
- **Outcome**: Outcomes capture the operational change to the problem situation due to the capability being delivered
- **Impact:** Impacts provide the “so what” behind the capability being delivered. It sums up why the capability matters, how it seeks to achieve the desired end state, and why we are taking on this endeavor

6 Additive Manufacturing Technology Roadmap

The resulting roadmap strategy outlines a portfolio of work containing 21 projects over a 57-month duration. The portfolio's projects are outlined in Table 11, visualized in Figure 18, and discussed in detail within. Representative breakdowns at the swim lane and project levels are depicted in Figure 19 and Figure 20.

Table 11: Roadmap Portfolio

Swimlane	Project	Description
Scale Current State	Scale Sand Printing Capability	Disseminate leading practices and promote the adoption of 3D printed sand molds/cores
	Scale Pattern Printing Capability	Develop and disseminate leading practices and promote the adoption of 3D printed patterns for casting
	Ensure Operational Recovery of Industrial Production	Establish a scalable sourcing model for AM industrial equipment replacement parts to keep critical production equipment running
	Scale-Up Strategy via Prototypes and Fixtures	Define an optimal dissemination strategy for design/ deployment guides through prototypes and fixtures
Prove Production Capability	Develop Binders for High Temperature Sand Casting	Develop enhanced binder materials and strategies to drive the processing efficiency of 3D printed sand
	Ceramics for Pattern-less Investment Casting	Mature ceramic AM technology to enable rapid pours into integrated shells and cores
	Conformal Cooling Implementation Tools	Develop and disseminate performance-enhancing tools for implementing AM conformal cooling
	Methods to Add Features with DED	Establish, assess, and demonstrate transferable capability to add complex geometric features to forgings
	Methods to Add Functional Surfaces	Establish, assess, and demonstrate the transferable capability to add functional surfaces to forgings
	DED and Cold Spray for Tooling Repair	Establish methods for planned and unplanned tooling repair and modification applications
	Pilot Process for Printing Forging Preforms	Pilot the industrialization of AM preforms to expedite the forging process for low-volume components
	Pilot Process for Printing Forging Dies	Pilot the industrialization of AM dies to expedite the forging process for low-volume components

Swimlane	Project	Description
Build Digital Foundation	Rapid Printed Preform Validation with Simulation	Enable optimized process setups with predictable performance using preforms with heterogenous microstructures
	Guidance for AM Data Collection	Establish data infrastructure and application-based guidance to collect and store data spanning AM process flows
	Pilot a Digital TDP/CAD Stockpile Program	Accelerate the creation of TDPs and CAD models for legacy components by building a program of record for continued conversion
	Simulation-Supported Lifetime Recommendation	Develop material and geometric performance software solutions to integrate into DoD process flows
Supporting Efforts	Techno-Economic Frameworks	Drive AM utilization by establishing frameworks that clearly define when, where, and how to print feasibly and economically
	DfAM Guides	Enable confident and efficient usage of AM by documenting proven design rules across parts, tooling, and accessories
	Dissemination & Training	Scale the adoption of technical development with focused and strategic communication to build a pipeline of SMMs ready to leverage AM capabilities
	Process Deployment Guides	Build delivery mechanisms for technical development by documenting clear and tested procedures for implementing and controlling AM processes on the shop floor
	Material Datasets	Enable cross-functional sharing with standardized management and storage of material data gathered during development activities

The efforts comprising the portfolio of 21 projects result in the study of 40 material-process combinations, including the assessment of 52 individual components against their respective first article requirements to demonstrate the AM capabilities developed. The crucial need to scale AM capabilities and drive their adoption is addressed through 25 transferability pilots demonstrating the ability to reproduce key outcomes and five production pilots to stress test development in real production environments.

The roadmap detailing all swim lanes and projects is publicly available and housed as a deliverable in America Makes CORE (Project 5536.000). Along with contextual information (e.g., swim lane definitions), the complete document contains the following:

- Additive Manufacturing Technology Roadmap (see Figure 18)
- Four swim lane breakdowns (see representative example in Figure 19)
- Twenty-one project breakdowns (see representative example in Figure 20)

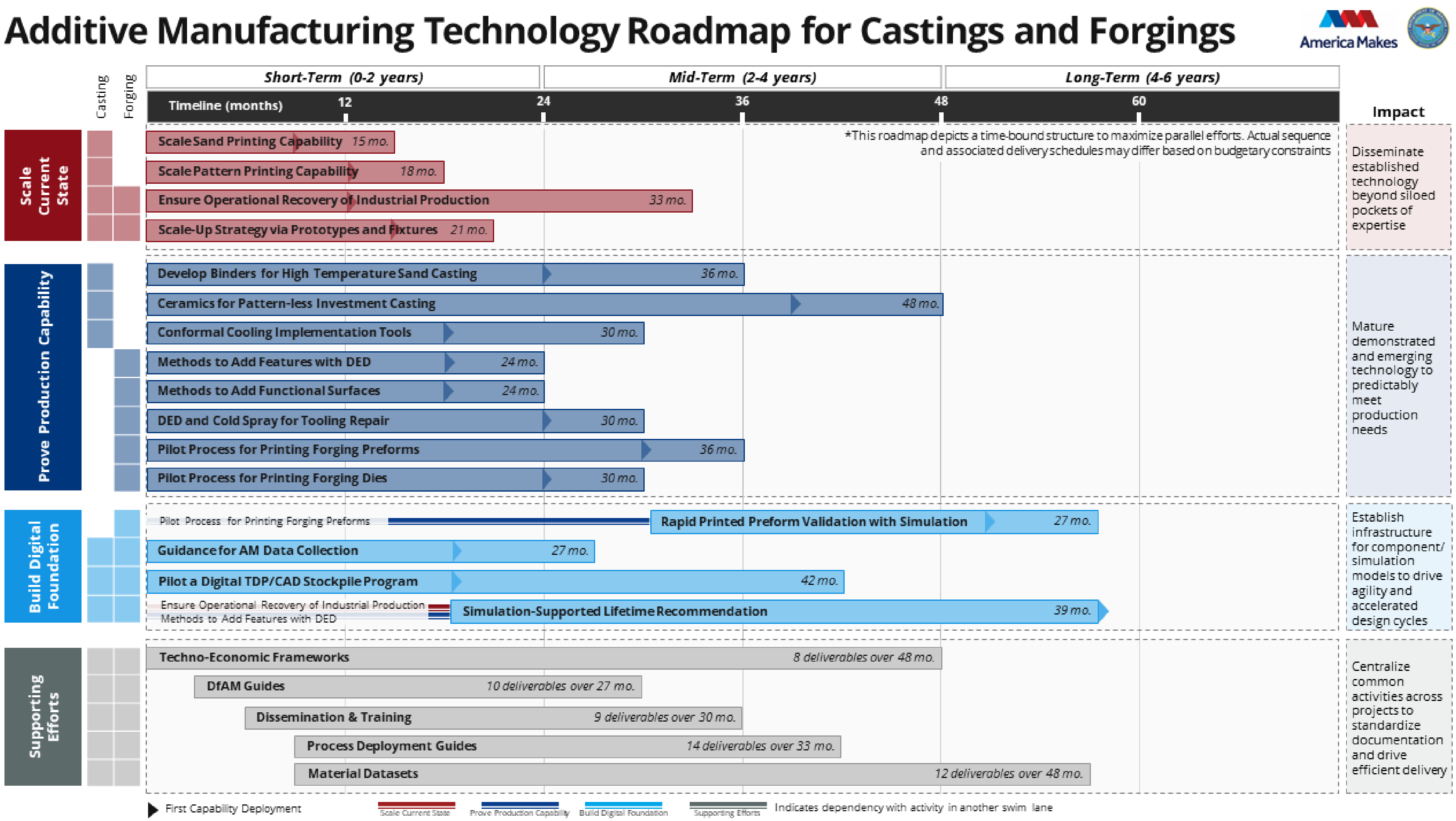


Figure 18: Additive Manufacturing Technology Roadmap for Castings and Forgings

Prove Production Capability

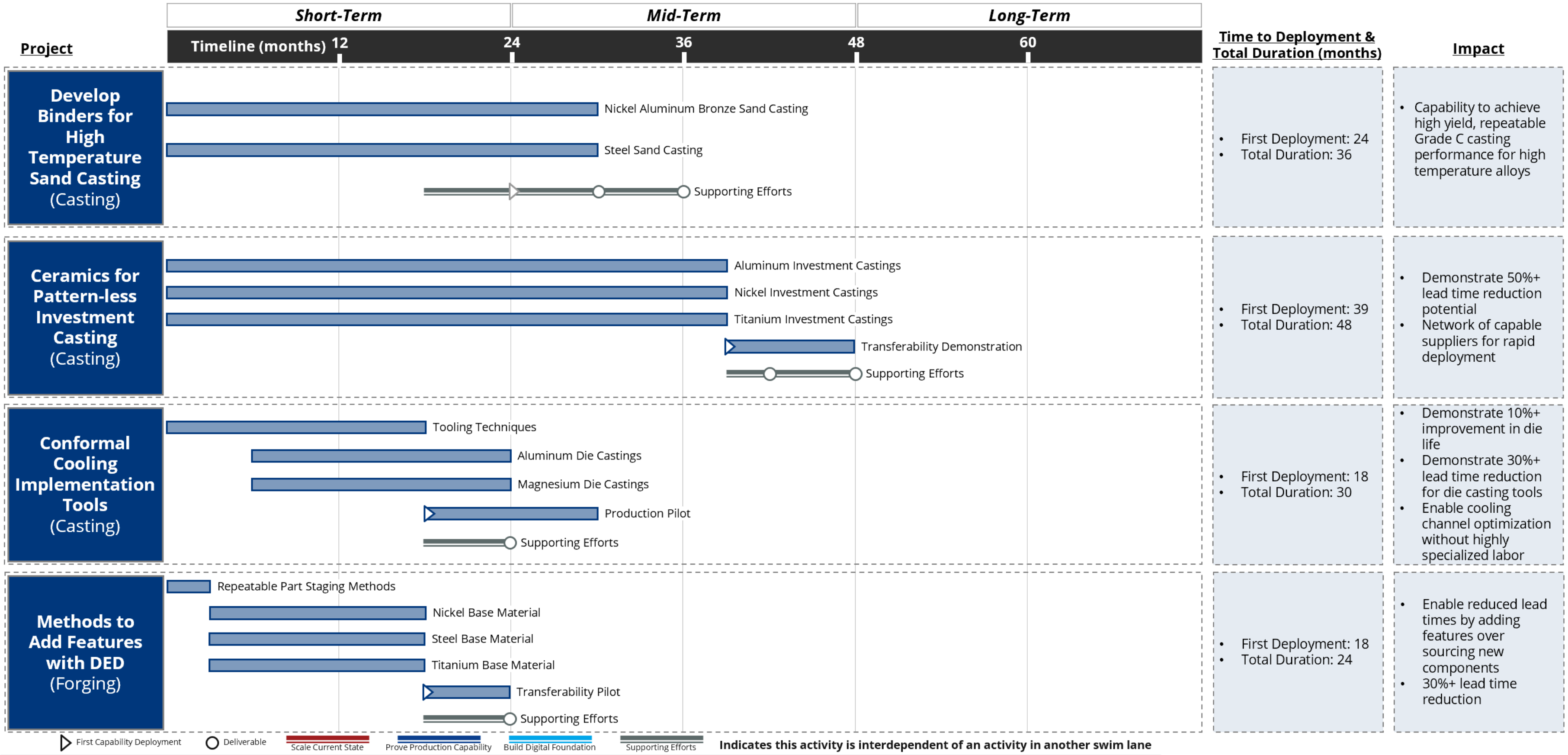
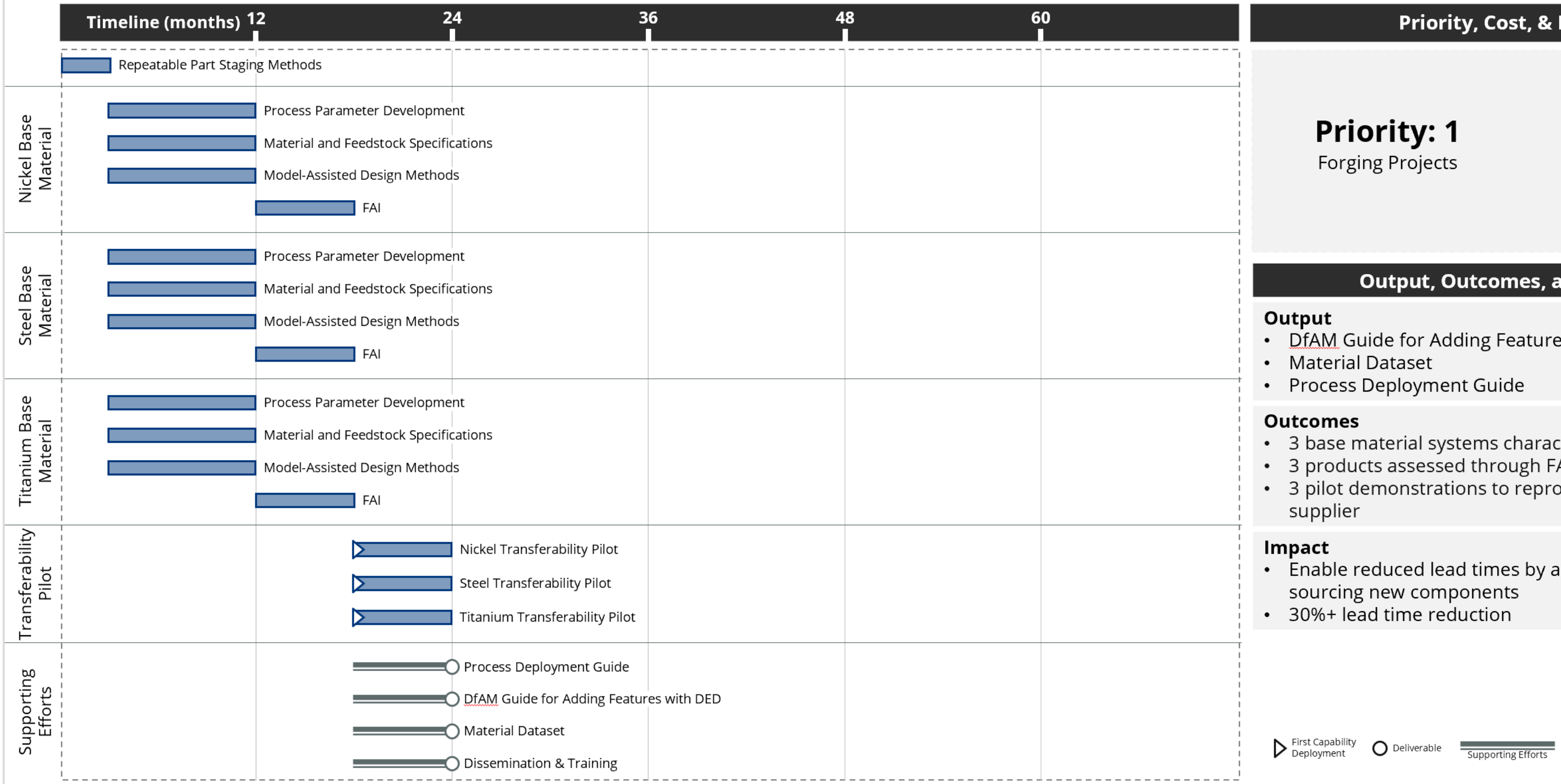


Figure 19: Representative Swim Lane Breakdown

Methods to Add Features with DED

Established, assess, and demonstrate transferable capability to add complex geometric features to forgings

Casting / Forging



Priority, Cost, & Duration

Priority: 1
Forging Projects

24 Months
Total Duration

Output, Outcomes, and Impacts

Output
- DfAM Guide for Adding Features with DED
- Material Dataset
- Process Deployment Guide

Outcomes
- 3 base material systems characterized
- 3 products assessed through FAI
- 3 pilot demonstrations to reproduce outcomes at new supplier

Impact
- Enable reduced lead times by adding features over sourcing new components
- 30%+ lead time reduction

Figure 20: Representative Project Breakdown

6.1 Project Descriptions

Detailed descriptions that address each project's context, overall goals, and summarized outcomes are provided below. Full project breakdowns are included within the complete roadmap document, housed as a deliverable in America Makes CORE (Project 5536.000).

6.1.1 Scale Current State

Scale Sand Printing Capability

Sand printing is currently industrialized, but its use is limited amongst the sand casting community. This project aims to promote the adoption of 3D printed sand molds and cores across the DIB by collecting and sharing leading practices. To reduce development cycles and streamline use at scale, the project will explore model-assisted design methods and first article inspection for low-temperature alloys. Expanding the adoption of sand printing will positively impact throughput and increase the supply base quoting on low-volume DoD parts.

Scale Pattern Printing Capability

Technologies for printing investment casting patterns are currently industrialized, but these capabilities are not broadly utilized across small and medium manufacturers. This project drives the adoption of AM patterns by identifying and packaging leading practices across design, post-processing (e.g., burnout), and process control. Critical test cases in Aluminum and Nickel are tested through FAI to prove that part requirements can be met. Leading practices will be transferred to different organizations within the investment casting community to demonstrate that the capability is reproducible and meets specifications at scale.

Ensure Operational Recovery of Industrial Production

Supply chain challenges for DoD parts are compounded by equipment downtime and sourcing replacement parts. AM provides a unique solution to bridge the gap by printing equipment replacement parts. This project establishes a scalable sourcing model by constructing a supplier network for industrial equipment replacement parts to keep critical production equipment running. A common data model needs to be established to drive agility and flexibility to source across the network. Following production trials, this project will document the process to build a shared understanding of when and how to use AM to print industrial replacement parts.

Scale-Up Strategy via Prototypes and Fixtures

Printed prototypes and fixtures are not used at scale across the DIB despite being more established and accessible than other AM use cases. This project seeks to expand the use of AM fixtures (i.e., fixtures for machining, assembly, and inspection) in production settings without posing changes to the end part's form, fit, and function. This project also seeks to expand the use of AM prototypes to enable parallel-path development and reduce NRE costs. Dimensional capability and repeatability will be assessed while measuring and quantifying the benefits of using AM prototypes and fixtures. Unique DoD needs that can be addressed with AM prototypes and fixtures will need to be identified concurrently with capability demonstration, and a strategy for expanding adoption will be developed.

6.1.2 Prove Production Capability

Develop Binders for High Temperature Sand Casting

The existing binder materials on the market for sand printing can constrain the use of sand printing for casting. This project seeks to advance the capability of today's sand printing technology by developing enhanced binder materials and identifying process controls and recipes to reduce binder use and streamline burnout processes. By developing and testing new binders, sand printing for casting will expand production use to include high-temperature alloys.

Ceramics for Pattern-less Investment Casting

Printed ceramics can provide significant lead time reduction for investment casting, removing the need for patterns and the associated labor costs. This project directs the development of emerging ceramic AM technologies towards DoD needs to ensure that the material portfolio, casting performance, and build envelope are capable and repeatable. To realize these benefits in production, leading practices for the process flow (including model-assisted design and thermal processing) are documented, tested, and transferred to prove a reproducible and scalable capability.

Conformal Cooling Implementation Tools

The ability to conformally cool die casting tooling poses many operational benefits, including die-life improvement and cycle time reduction. Furthermore, creating and optimizing tooling with conformal cooling channels is an expensive, iterative process that requires highly specialized labor. This project develops processes and tools to enable rapid, repeatable application and demonstrates improvements to key performance indicators. Included within the scope are digital tools to optimize cooling channel design, the necessary surface treatment techniques, and the associated lifetime of the die. Test cases across materials will be assessed through FAI to demonstrate and reproduce the technology’s benefits.

Methods to Add Features with DED

Complex forgings require multiple operations to arrive at a final net shape. This project explores how AM can be coupled with forging by adding geometric features with DED to reduce material use and speed up throughput. The project assesses the capability, establishes procedures, completes FAI, and culminates in a transferability pilot to demonstrate its use. By incorporating hybrid manufacturing, this project enables reduced lead times and opens machine capacity.

Methods to Add Functional Surfaces

This project explores how AM can be coupled with forging by adding functional surfaces with DED to improve part life on critical wear surfaces. The project assesses the capability, establishes procedures, completes FAI, and culminates in a transferability pilot to demonstrate its use. By incorporating hybrid manufacturing, this project extends product lifetime and reduces long-term demand.

DED and Cold Spray for Tooling Repair

Forging die repairs are customized jobs unique to the die condition and require highly specialized labor. This project explores how AM's flexibility can be applied to support rapid die repair through DED and cold spray technologies. Development is undertaken to define processes and parameters that ensure performance and dimensional requirements can be met. Dedicated efforts are undertaken to transfer and deploy this capability, proving the ability to scale. Delivery results in reduced lead times and extended die life.

Pilot Process for Printing Forging Preforms

The challenges of sourcing precisely sized raw materials can affect lead times for forgings, particularly for large components. This project pilots an industrialized solution to combine AM and forging process flows, using AM material as an input to forging. Capable of producing any shape based on a common raw material input, AM's flexibility creates an opportunity to increase forging throughput and potentially remove the number of reduction steps by printing near-net-shape preforms. Development is focused on ensuring these benefits can be realized while maintaining required performance, taking test cases through FAI, and running through production pilots.

Pilot Process for Printing Forging Dies

Raw material sourcing challenges are present for both parts and dies within forging. This project develops and tests methods for printing forging dies and die inserts to enable economical low-volume forgings by reducing engineering development and material costs for short-run tooling. Printing forging dies can leverage AM's speed and flexibility without changing the constituent material for the end component. The project focuses on ensuring that the die characteristics and forged part requirements can be met by taking critical test cases through FAI.

6.1.3 Build Digital Foundation

Rapid Printed Preform Validation with Simulation

Forging and testing AM preforms provides the foundation for using rapid, near-net-shape forgings for low volumes. This project builds on these efforts to enable predictive performance for AM preforms, reducing development cycles and potentially the number of forging steps by shaping the preform closer to the final geometry. Initial work in model-assisted design is expanded to include additional materials, processes, and applications to broaden the window in which AM preforms can rapidly respond to DoD needs.

Guidance for AM Data Collection

AM processes can produce troves of data, which can be used for several purposes. For the DoD, no clear guidance on which data should be collected based on a particular use case and set of performance requirements exists. This project creates common frameworks for recommended data collection across AM modalities and process steps, from feedstock to machine sensors, to drive a standardized approach. Part characteristics are considered, and representative test cases across performance and risk levels are assessed in scope.

Pilot a Digital TDP/CAD Stockpile Program

Legacy components lack digital models, which lengthens the lead time for replacement components. This project focuses on developing repeatable processes for drawing conversion and generating a stockpile of CAD models. Documenting and validating the process through FAI will support building a program of record for continued conversion.

Simulation-Supported Lifetime Recommendation

The ability to produce a short-term component or extend the life of an existing one by adding lost features poses significant supply chain benefits. Still, it is accompanied by critical questions about component lifetime. This project focuses on leveraging simulation to establish recommendations for short-term and extended lifetimes of components leveraging AM. Multiple sets of material and process combinations are studied for each use case, constructing material datasets to calibrate and refine simulation models against physical results. The project results in a guidance document to promote standard practices across the AM modalities and processes studied.

6.1.4 Supporting Efforts

Techno-Economic Frameworks

Understanding when to incorporate AM into existing processes is a hurdle to increasing production at scale. By establishing frameworks that clearly define when, where, and how to print, the DIB can increase AM utilization and realize the impacts generated through other projects on the roadmap.

Design for Additive Manufacturing Guides

AM offers design freedoms beyond traditional manufacturing that are not always evident to designers. Generating DfAM guides will enable confident and efficient AM usage by documenting proven design rules across parts, tooling, and accessories.

Dissemination and Training

Developing the knowledge base across CF industries is critical to successfully leveraging AM to reduce lead times. This project is a centralized effort to scale the adoption of technical solutions with focused and strategic training.

Process Deployment Guides

The technical projects on the roadmap generate leading practices for successfully deploying and using AM in production settings. This project documents the tested procedures for implementing and controlling AM to promote scaling the technology across the DIB.

Material Datasets

Data generated across projects can provide cross-pollination and serve as the foundation for future analytics and predictive efforts. This project standardizes the management and storage of the material data gathered during development activities to promote knowledge sharing across the roadmap's efforts.

7 The Path Forward

While the creation of the roadmap has established a path forward, sustained focus and investment are needed to create an enduring network of AM capability within casting and forging facilities of all sizes nationwide.

The technical capabilities developed by the projects on the roadmap need to be intentionally transferred out of demonstration and into production, with persistent efforts to incentivize adoption among the industrial base. Without continued focus and investment, progress will be halted, and immediate and growing implications will be posed to the current state.

7.1 Consequences of Inaction

Without a solution to predictably acquire low-volume castings and forgings, the DoD will continue to face significant warfighter readiness issues on widespread and aging platforms. Furthermore, the challenges posed by labor availability and economic headwinds will likely worsen no-bid scenarios, further driving purveyors of casting and forging towards high-value and high-quantity orders.

In addition to process flexibility, a key benefit of AM is its flexibility in utilizing standard material forms across parts of all shapes and sizes. This mitigates raw material sourcing challenges in which specifically sized stock is required for production. As geopolitical turmoil with Russia continues, the availability of key raw materials may be further compromised, affecting all downstream steps and the sourcing responsiveness of casting and forging supply chains at large.

Global competitors, including China, are also developing and deploying substantial advanced manufacturing skills and technologies. The US risks falling behind these competitors in the drive toward manufacturing and supply chain resiliency without continued investment.

Finally, the creation of this roadmap has regularly convened experts and key stakeholders across the CF ecosystems, building awareness of these critical issues and momentum toward solving them. While inaction contributes to significant consequences, it also inhibits the grassroots support and momentum for solving these issues, which this effort has ignited over the past eight months of cross-industry collaboration.

7.2 Consequences of Narrow Action

Focusing actions solely on technology development will not address the full scope of the sourcing problems for low-volume castings and forgings. If policy and people-related considerations are not addressed, the use of new technology could even compound existing issues. Throughout this effort, subject matter experts consistently and repeatedly expressed the overarching bottlenecks associated with qualification and workforce. Without dedicated efforts to assess and address these issues, backlogs for component acceptance will grow, fed by the flexibility of technology solutions and stifled by procedural restrictions.

Challenges with qualification were specifically identified as major bottlenecks. There are many aspects to qualification that fall across individual components, processes, and suppliers. They affect the management of legacy components with cost-prohibitive certification requirements, aversion to process changes, and lengthy approval processes.

Collectively, these conditions limit the supplier base and significantly reduce economic incentives for bidding on low-volume orders. There is no "one size fits all" solution to these challenges, as qualification holds different meanings depending on the design authority and component requirements. This large and interwoven space will not be adequately addressed without focused action.

To deploy solutions and realize the benefits offered by advanced technology, complementary and enduring workforce capabilities are needed. Technological solutions can address ongoing labor shortages and drive labor efficiency, but only to a certain point. The existing shortages today underscore the need to upskill the workforce, not only for the sake of productivity but to drive retention and growth of skilled labor availability. The existing workforce is an asset that should receive continued and focused development to foster its growth.

7.3 No Regrets Next Steps

The roadmap provides America Makes, the DoD, and the US with the critical infrastructure and strategic vector it needs to build an enduring and broad AM capability in casting and forging facilities nationwide. With continued funding and detailed execution, this program will develop and deploy these capabilities to support warfighter readiness through economically viable, low-volume castings and forgings.

There are three "No Regrets Next Steps" necessary for the long-term success of an AM-augmented, agile, and resilient supply chain for the DoD:

Lower Adoption Risk	Invest in Technology Deployment	Incentivize Expertise
While the benefits and potential of AM are well known, so are many examples of failed printing pilots. Many risks driving these failures are seemingly hidden, as they sit adjacent to the printing process itself. Disseminating resources and tools to make informed decisions on when to use AM and to upskill staff without major financial investment will support the wider adoption of AM technologies among small and medium manufacturers.	Implementing AM successfully requires much more than a capable printer. Continued focus on transferring key outcomes out of the lab and onto the shop floor is crucial to drive familiarity with AM and create true learning environments for users. Guidance for everyday process control should be established and provided as oversight to onboard new technology.	Early adopters of AM have made significant investments to develop their internal capabilities and intellectual property. These key examples have the potential to be replicated at scale but can only be done so by establishing incentives for knowledge sharing.

Appendices

Appendix A- Literature Review Subtopics

Topic	Subtopic
Material Performance	Static Mechanical Properties
	Dynamic Mechanical Properties
	Corrosion Resistance
	Surface Finish
	Material Testing Methods
	Microstructure
Novel Materials	Novel Alloys
	Tailored Microstructure
	Metamaterials
	Multi-Material
	Metal Composites
Part Qualification	Critical Defect Size
	In-Process Verification
	Qualification Methods
	Comparison to Traditional Processing
	Effect of Defect
	Design Considerations
Design Optimization	Assembly Consolidation
	Lightweighting
	Simulation-Driven Design
	Design for AM Principles
AM Process Optimization	Material Optimization
	Dimensional/Stress Optimization
	Speed/Throughput Gains
	Process Physics
	Energy Efficiency
	Selection Frameworks

Topic	Subtopic
Casting/Forging Augmentation	Printed Sand Molds
	Printed Tooling
	Conformal Cooling
	Printed Patterns & Shells
	Near-Net Shape Parts
Hybrid Manufacturing	Tool Repair
	AM & Machining
	Post-Processing
	Printing Additional Features
	In-Process Forming
In-Process Monitoring	Defect Detection
	Solidification Monitoring
	In-Process Data Analysis
	Image Processing Algorithms
	Computer Vision
	Parameter & Property Calculation
Non-Destructive Testing	Radiography
	Simulation Techniques
	Non-Destructive Data Analysis
	Smart Factory & Supply Chain
Digital Capability/Industry 4.0	Cloud Computing
	Artificial Intelligence
	Digital Twin
	Optimized Data Storage
	Scanning & Reverse Engineering
Technology Overview	Technology Overview

Appendix B- Interview Synthesis

From the interviews, approximately 400 data points were collected, categorized, and scoped according to the codes in Section 3.1.2. Figure 21 shows the distribution of L1 codes by community (left) and the percentage of interviewees in each community (right).

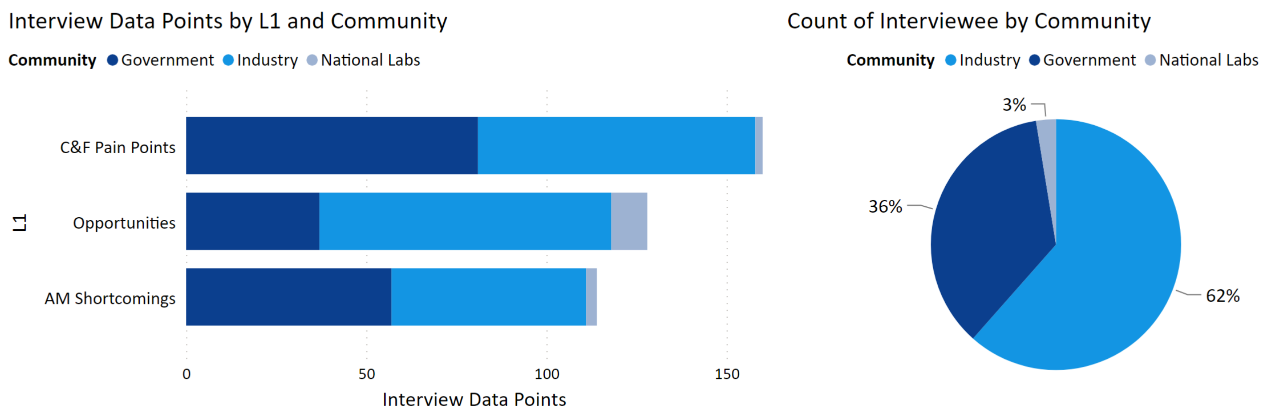


Figure 21: Interview Data Overview

Figure 22 details which CF pain point L3 codes were the focus areas for the Visioning Workshop. The bars are color-coded based on whether the category was a focus area for the workshop (maroon) or not (gray). While one of the roadmap's goals is increasing the productivity of labor hours in CF, increasing capacity through new facilities and employees is outside of its technical scope. Contracting, forecasting, demand, and regulatory constraints will not be addressed through additive manufacturing, making both out of scope for the Visioning Workshops. The challenges with NDT were from a labor and policy perspective, which are discussed in Section 7.2. Unique alloy requirements and tolerances for DoD parts, along with data management, are not process-specific and not a focus area for the workshops.

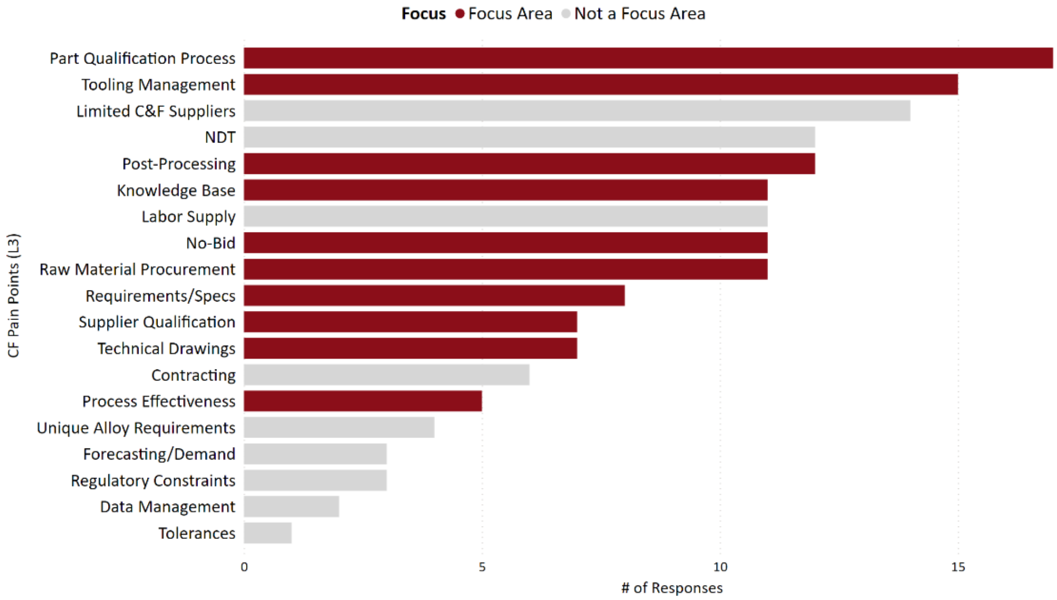


Figure 22: Interview Coding Data: Pain Points

Figure 23 details which opportunity L3 codes were focus areas for the Visioning Workshop. Most opportunity codes were focus areas for the Visioning Workshop, except for automation, new alloys, and pipeline. While automation is a technical solution, the scope of this roadmap is for augmenting casting and forging with additive manufacturing; another project is investigating improving the industrial base through automation. New alloy development for additive manufacturing is beyond the time horizon for this roadmap due to the amount of research required. Pipeline programs are not technical solutions and, thus, out of scope for this roadmap.

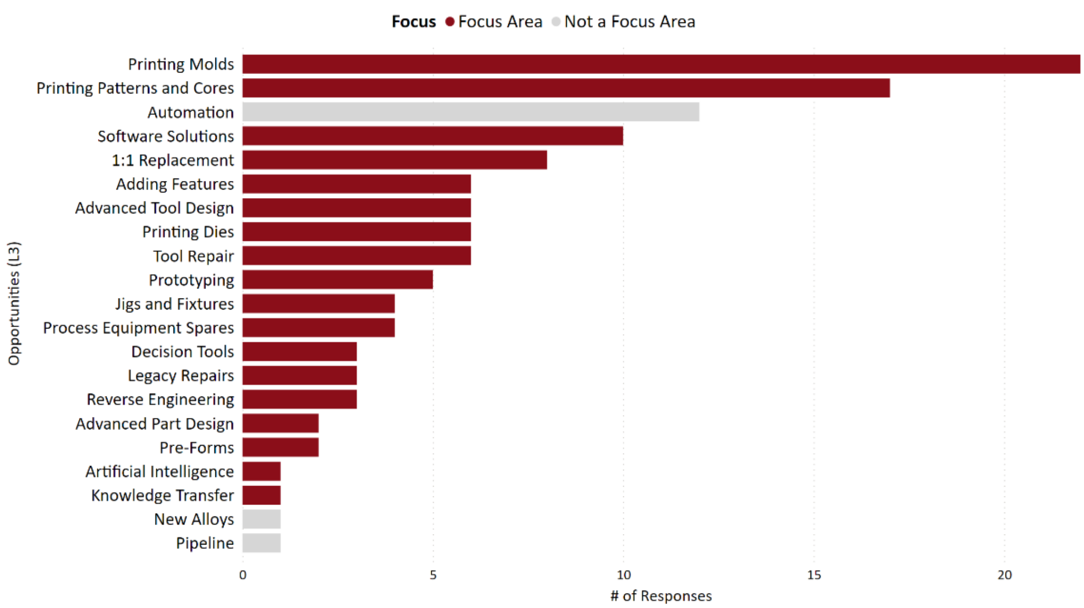


Figure 23: Interview Coding Data: Opportunities

Figure 24 details which AM shortcoming L3 codes were focus areas for the Visioning Workshop. In general, codes dependent on the printer manufacturer are not focus areas for the roadmap efforts; this includes economics, build volume, limited OEM printers, material sourcing flexibility, in-situ measurements, tolerances, and intellectual property. Material data will be a byproduct of the roadmap and, therefore, is not a focus area for the visioning workshop. Inherent material qualification is beyond the time horizon of the roadmap; within AM qualification, standards for AM use were a focus during the Visioning Workshop. Downstream machining was not a focus area for the workshops because it is not unique to additive manufacturing. Finally, regulations surrounding additive manufacturing are not technical challenges.

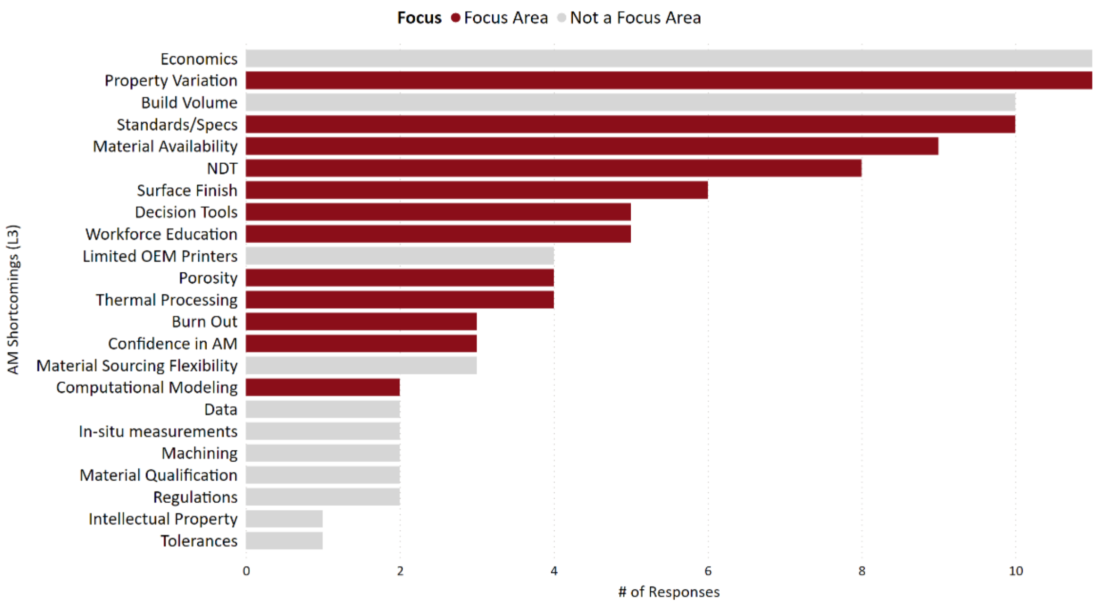


Figure 24: Interview Coding Data: AM Shortcomings

B.1 Visioning Workshop Input Data

Table 12: Visioning Workshop Inputs for Casting

Category	Workshop Input
Pain Point	The specifications for legacy parts are not always clearly defined and open to interpretation
	Needing to convert 2D drawings to 3D CAD models for legacy components
	First-pass yield/scrap can be a significant cost
	Tooling can be difficult to manage (e.g., long lead times, costs, wear, storage)
	The qualification process (design, prototype, inspect, and approve) can be challenging, lengthy, and costly
	Machining and grinding bottlenecks extend lead times
	Furnace capacity is lacking (e.g., vacuum furnaces and HT)
	Rework can be a significant bottleneck
	Raw material sourcing lead time from approved suppliers
	The wealth of knowledge in the industrial base is declining
	Bidding on low volumes is too risky (i.e., costs too high)
Opportunity	Reverse engineering tools to shorten design lead time
	Modeling and simulation tools to improve the design process
	Use additive manufacturing to produce a traditionally cast/forged part when needed
	Leverage AM design freedoms to generate complex designs or consolidate assemblies
	AM prototypes to speed up development activities and fixturing setups
	Use cold spray and DED to repair cast or forged parts (e.g., gear on a ring bearing)
	3D printing complex cores to combine multiple cores into one
	AM conformal cooling channels to assist with thermal management
	AM fixtures and jigs for post-processing/inspection setup
	Printing dies
	Printing tooling for wax injection
	Printing sand molds and cores
	Printing ceramic molds and cores
	Printing patterns
	Print CF equipment replacement parts to bridge long lead times and "stay in the fight"
	Develop tools/guides to assist with technology selection and design

Category	Workshop Input
AM Shortcoming	NDT standards for AM are not mature
	Decision tools are needed to assist with AM technology selection
	Guidance is needed to distinguish critical from non-critical components
	Not enough people know how to quote for AM tooling
	Not enough engineers know leading AM design practices
	There is limited trust in AM
	Porosity needs to be better understood to achieve proper densities in AM parts
	AM needs more consistent material properties to compete with CF
	Specifications and standards for AM qualification need to be established and be reasonable
	Surface finish can be a barrier for AM
	Need better processes for binder burnout
	Need better processes to burn out SLA/printed wax patterns from shell
	More HIP capacity is needed (hot isostatic pressing)
	AM outcomes need to be more predictive
	The materials we need are not available for AM

Table 13: Visioning Workshop Inputs for Forging

Category	Workshop Input
Pain Point	The specifications for legacy parts are not always clearly defined and open to interpretation
	Needing to convert 2D drawings to 3D CAD models for legacy components
	Test runs can be a significant source of scrap
	Tooling can be difficult to manage (e.g., long lead times, costs, wear, storage)
	The qualification process (design, prototype, inspect, and approve) can be challenging, lengthy, and costly
	Machining and grinding bottlenecks extend lead times
	Furnace capacity is lacking (e.g., vacuum furnaces and HT)
	Rework can be a significant bottleneck
	Raw material sourcing lead time from approved suppliers
	The wealth of knowledge in the industrial base is declining
	Bidding on low volumes is too risky (e.g., costs too high)

Category	Workshop Input
Opportunity	Reverse engineering tools to shorten design lead time
	Modeling and simulation tools to improve the design process
	Use additive manufacturing to produce a traditionally cast/forged part when needed
	Leverage AM design freedoms to generate complex designs or consolidate assemblies
	AM prototypes to speed up development activities and/or fixturing setups
	Use AM to add features or high wear layers to forgings to enhance performance
	Use cold spray and DED to repair cast or forged parts (e.g., gear on a ring bearing)
	Use AM pre-forms to eliminate upstream processes
	AM fixtures and jigs for post-processing/inspection setup
	Printing dies
	Print CF equipment replacement parts to bridge long lead times and "stay in the fight"
	Use AM for tool repair and keep manufacturing "in the fight" (ex: DED/cold spray for die repair)
	Develop tools/guides to assist with technology selection and design
AM Shortcoming	NDT standards for AM are not mature
	Decision tools are needed to assist with AM technology selection
	Guidance is needed to distinguish critical from non-critical components
	Not enough people know how to quote for AM tooling
	Not enough engineers know leading AM design practices
	There is limited trust in AM
	Porosity needs to be better understood to achieve proper densities in AM parts
	AM needs more consistent material properties to compete with CF
	Specifications and standards for AM qualification need to be established and be reasonable
	Surface finish can be a barrier for AM
	More HIP capacity is needed (hot isostatic pressing)
	AM outcomes need to be more predictive
	The materials we need are not available for AM

Appendix C- Expertise & Availability Survey Questions

As part of the Strategic Communications & Outreach plan, prospective workshop attendees were asked to complete a brief survey where they indicated what processes and materials they had experience with and which workshop sessions they planned to attend. The results were compiled and shared with America Makes for potential future collaboration. The questions are below:

1. Please provide the following information:
   - First Name
   - Last Name
   - Email Address
   - Organization
2. What processes do you have experience in? (You can select multiple.)
   - Investment Casting
   - Die Casting
   - Sand Casting
   - Open Die Forging
   - Close Die Forging
   - Ring Roll Forging
   - Additive Manufacturing
   - Other
   - Not Applicable
3. If you selected other, please list your relevant experience.
4. Which materials do you have experience in? (You can select multiple.)
   - Steel
   - Stainless Steel
   - Aluminum
   - Titanium
   - Nickel Alloys
   - Copper
   - Bronze
   - Magnesium
   - Iron
   - Other
   - Not Applicable
   - If you selected other, please list relevant materials you have experience with.
5. Which of the following in-person Visioning workshops are you able to attend? Note: We are asking participants to attend one of each workshop – one for Visioning and one for Functional Analysis.
   - Milwaukee, WI on March 16
   - Youngstown, OH on March 29
   - Unable to attend either
6. Which of the following in-person Functional Analysis workshops are you able to attend? Note: We are asking participants to attend one of each workshop – one for Visioning and one for Functional Analysis.
   - Youngstown, OH on May 10
   - Milwaukee, WI on May 17
   - Unable to attend either

Appendix D- Visioning Workshop Output

Deloitte.

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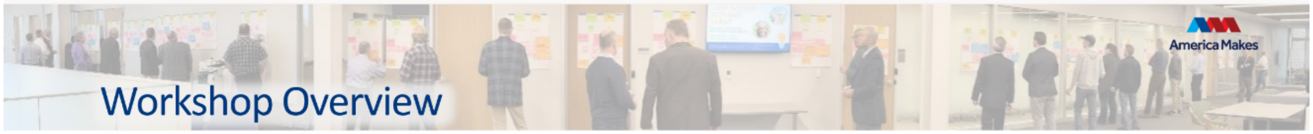

Workshop Overview

WORKSHOP INPUTS

From **41+** expert interviews...

36 Distilled Data Points + **95** Attendees Representing **75** organizations

WORKSHOP OUTPUTS

54+ Goal Statements → **5** Key Themes

KEY THEMES:

- **AM for Tooling** — **AM for tooling is the most feasible solution** as the final part is not being altered easing qualification requirements while speeding up the time to get tooling and lowering the cost
- **Confidence in AM** — Due to underdeveloped standards and limited characterization of the material properties there is a **general lack of confidence in the repeatability of AM** compared to casting and forging
- **Modeling and Simulation** — Desire to **improve modeling and simulation tools** to improve decision making, increase confidence in part performance, and speed up the qualification process
- **Assisted 3D model creation** — Desire for **improved tools** to assist with converting **2D drawings to 3D CAD models** when the drawing exists and **tools for reverse engineering** when it does not
- **Workforce Enablement** — **Workforce enablement** was cited as a current pain point with C&F, and as a gap to implementing AM solutions

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Workshop Key Takeaways

Post workshop synthesis yielded potential initiatives to alleviate the common challenges of workforce shortages, lengthy qualification processes, lack of 3D CAD models and lack of well-defined TDP's for legacy components

Themes	Potential Initiatives
AM for Tooling	• **Capture AM accelerators** for tooling where they exist and **develop/pilot them** where they do not – Forging: *Tool repair, adding features (to part/pre-form), printing pre-forms / dies / tooling inserts* – Casting: *Printing ceramic molds, sand molds & cores, patterns, and dies*
Confidence in AM	• Create **frameworks and decision guides/tools** to facilitate AM accelerator selection • Support collaborative efforts to **produce and characterize AM materials** • **Promote awareness** of AM accelerators and increase accessibility
Modeling and Simulation	• **Understand the investment landscape** of private and government funding for **AM simulation tools** and ensure alignment with DoD needs for C&F • Identify missing data required to **improve simulation capability, accuracy, and speed** • Invest in development areas where there are specific gaps
Assisted 3D model creation	• **Invest in 2D to 3D conversion** & **reverse engineering tools** to increase accessibility • Purchase the final part 3D model when legacy part data needs to be updated
Workforce Enablement	• Regardless of the solution that is selected and implemented, **casters, forgers, and designers will need to be trained** on how to use the new tools at their disposal • Prioritize projects that increase the **effectiveness of labor**

To promote the adoption of these AM accelerators, consideration will need to be given to the level of financial support required to retool the SMM's and increase accessibility

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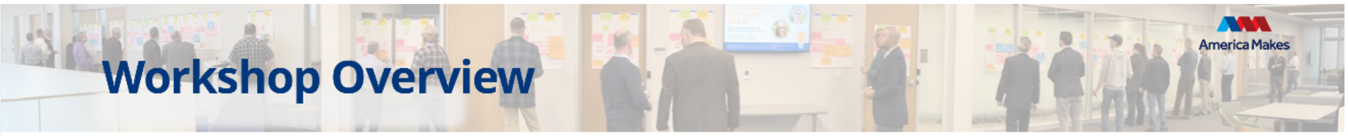
Appendix E- Functional Analysis Workshop Output



Workshop Overview

America Makes

TOPICS & EXPERTISE

14 Projects + **86** Attendees across **60** organizations

EXECUTION PLANS

85 Validated / Modified Initiatives **142** Added Initiatives +

PRELIMINARY PRIORITIZATION

- Impact & Effort Scoring
- Cost
- Duration
- Material Priorities

Where to Focus

Casting	Sand molds and cores
Casting	Printed patterns
Casting	Consolidated casting cores
Casting	Printed ceramics
Casting	Conformal cooling channels
Casting	Consolidated assemblies
Forging	"Bridge" components
Forging	DED and cold spray for repair
Forging	AM preforms
Forging	AM dies
Forging	Adding features and wear layers
Shared	TDPs and CAD Models
Shared	AM simulation
Shared	Prototypes and fixtures

What's Needed to Succeed

Path to Print
Playbooks to deploy AM technology for patterns, molds, dies, and repairs

Shared Understanding
Common guidance on when to print, capable vendors, and how to measure performance

Integrated Tools
AM material property predictions as input to broadly used software

Digital Foundation
Common TDP structure with processes to build digital stockpiles

Sustainable Training
Accessible AM resources contained and grown within Casting and Forging communities

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Workshop Results

Data across workshops has been synthesized into preliminary priorities and focused projects

	Top Preliminary Priorities	Key Deliverable	Impact
Casting	1. **Sand molds and cores**	Standardized binder burnout cycles	• Reduced NRE cost • Reduced variation • Removed bottlenecks with parallel path • Improved confidence in AM outcomes
Casting	2. **Printed ceramics**	Guidance for production testing and control	
Casting	3. **Conformal cooling channels**	High tolerance surface treatment techniques	
Casting	4. **TDPs and CAD models**	Common TDP structure(s)	
Casting	5. **AM simulation**	Database(s) with AM material properties	
Forging	1. **"Bridge" components**	Risk-based assessment framework for acceptance	• Extended tooling life • Simplified supply chain • Reduced cost/time of tooling repair • Increased process flexibility
Forging	2. **Adding features and wear layers**	Process guidance for mating dissimilar materials	
Forging	3. **DED and cold spray for repair**	Framework for AM tool repair	
Forging	4. **AM preforms**	DoD test part pilot	
Forging	5. **AM dies**	AM die/insert pilot	

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Appendix F- Acronyms

Acronym	Definition
AM	Additive Manufacturing
CAD	Computer-Aided Design
DED	Directed Energy Deposition
DIB	Defense Industrial Base
DOD	Department of Defense
LPBF	Laser Powder Bed Fusion
NDT	Non-Destructive Testing
NRE	Non-Recurring Engineering
OIB	Organic Industrial Base
OEM	Original Equipment Manufacturer
OSD	Office for the Undersecretary of Defense
ROM	Rough Order of Magnitude
TDP	Technical Data Package

Appendix G- Coding Definitions

L1 Code	L2 Code	L3 Code	Definition
CF Pain Points			Challenges with the casting and forging supply chain that are lengthening lead times
	Supplier Management		The administrative portion of the value chain where the DOD and their suppliers ensure requirements (i.e., quoting, contracting, regulatory, etc.) are met
		Limited CF Suppliers	The reduction in the industrial base impacting the number of foundries that can meet the DOD requirements
		Contracting	The process to arrive at a written agreement between the DOD and the foundry or a Prime and the foundry to produce parts
		No-Bid	The situation where foundries elect to forego bidding on a DOD request and the reasons for declining to bid
		Supplier Qualification	The process to qualify that a supplier meets the certification requirements and can reliably produce parts with a specific process and material (this is not specific to a particular part or order)
		Forecasting/ Demand	The challenges with getting the right information to accurately forecast demand and manage variability
		Regulatory Constraints	Constraints that foundries have to follow to produce parts for the DOD either based on government acquisitions (like FAR) or the types of parts being produced (like ITAR)
	People		Challenges with the supply chain that are with the workforce-based
		Knowledge Base	The reduction in the knowledge to design, produce, and inspect parts produced by foundry
		Labor Supply	The situation where it is difficult to find or keep people capable of supporting production
	Operations		The portions of the value chain where materials are prepared for processing upstream of the casting and forging processes and downstream where further processing is required to get to the finished part
		Raw Material Procurement	Difficulty sourcing materials on time for use in casting and forging
		Part Qualification Process	The process that ensures the produced part meets the standards and specifications outlined

L1 Code	L2 Code	L3 Code	Definition
		Post-Processing	The production steps downstream of casting or forging a part that are required to get the part the final dimensions and properties
		NDT	Non-destructive testing to inspect the part for dimensions and defects
	Materials and Process		The material being processed, the portion of the value chain where casting and forging processing of materials is performed (i.e., casting and forming), and the tooling and equipment associated with that process are managed
		Process Effectiveness	The overall effectiveness of the process that can be broken down into yield impacts, downtime impacts, and impacts on processing speed
		Unique Alloy Requirements	Requirements that are unique to a specific material. This can include machinery requirements that are unique for a specific alloy
		Tolerances	The allowable deviation from nominal dimensions as specified by a part drawing or model. These tolerances can be exceptionally tight in some cases, making it difficult to repeatably produce a part that meets specification
		Tooling Management	Challenges associated with managing tooling which include the cost of tooling, the lead time to produce tooling, tooling maintenance, and tooling storage
	Digital Infrastructure		Digital information required throughout the production process
		Requirements/ Specs	The defined requirements and specifications needed to produce a part to meet the final form, fit, and function as intended
		Technical Drawings	The 2D part drawings and lack of 3D models required to produce the intended part
		Data Management	Transferring, storing, retrieving, and utilizing product and process data

L1 Code	L2 Code	L3 Code	Definition
Opportunities			Different ways advanced technologies can be leveraged to address the casting and forging pain points with a focus on AM
	Tooling		The application of AM to develop molds, cores, patterns, jigs and fixtures, anything that helps make the part without printing the direct part. Benefits include reduced lead time and cost for low volumes and subsequent tooling management.
		Printing Patterns and Cores	Use of AM to print inserts, patterns, and cores for casting. Includes sand cores for sand casting, SLA/wax patterns, and wax/ceramic cores for investment casting. This is typically one step further upstream from directly printing the molds
		Printing Molds	Use of AM to directly print the mold. Includes printing sand molds for sand casting and ceramic molds for investment casting
		Jigs and Fixtures	Use of AM to print jigs and fixtures to support post-processing, inspection, and testing processes
		Printing Dies	Use of AM to print or partially print dies for forging, die casting, and injection molding
		Tool Repair	Use of AM to repair tools. Primarily consists of the use of cold spray and DED for forging dies or die cast tooling
		Process Equipment Spares	Use of AM to print replacement parts for production machinery that are difficult to procure quickly
		Advanced Tool Design	Use of AM to add advanced and precise tooling features. Examples include conformal cooling chambers, complex internal geometries, and assembly consolidation
	Direct Printing		The application of AM to directly print the part to meet the desired form, fit, and function or to enhance part performance through advanced design or novel materials
		Prototyping	Use of AM to develop a prototype part for conceptual use or functional testing
		1:1 Replacement	Use of AM to directly print a metal part. Primarily includes the use of LBPF, binder jet, MELD, and DED technologies
		Advanced Part Design	Use of AM to generate higher-performance designs. Examples include printing complex geometries and assembly consolidation
		New Alloys	Use of AM to generate components using novel materials with the intention of increasing overall component performance

L1 Code	L2 Code	L3 Code	Definition
	Hybrid Manufacturing		Using a combination of traditional and advanced manufacturing techniques to drive throughput or enhance the performance characteristics of a part
		Adding Features	Use of AM to add features to a traditionally manufactured part. Benefits include reduced material waste and lead time
		Pre-Forms	Use of AM to print near net-shaped material for the forging operations with the intent to eliminate upstream forming and upsetting processes
		Legacy Repairs	Use of AM to repair the end part. Primarily consists of use of cold spray and DED. Similar to tooling repair
	Digital		Use of digital or automated solutions that augment labor and increase throughput or development
		Reverse Engineering	Building a 3D CAD model directly from a legacy part. This can include the use of sophisticated scanning systems to pull dimensions
		Artificial Intelligence	The use of AI to process large amounts of data and flag exceptions to reduce human load and increase throughput
		Software Solutions	The use of software tools to increase throughput. Can include but not limited to simulation and design software
		Automation	The use of capital to reduce labor in a process. Includes the use of automated inspection systems, robotics for post-processing, and even refurbishing older equipment to improve throughput
	Workforce Development		Initiatives that drive the expansion of capabilities among the workforce either by increasing the quantity of available labor or expanding the knowledge base through training
		Pipeline	The deployment of programs intended to stimulate the talent pipeline and increase the availability of skilled labor
		Knowledge Transfer	Facilitating the transfer of knowledge through improved documentation or enhanced collaboration between different skillsets and talent pools
		Decision Tools	Developing and deploying tools that help drive efficient decisions in the selection of the appropriate process technology to use for a given part

L1 Code	L2 Code	L3 Code	Definition
AM Shortcomings			Gaps with AM and advanced technologies that impact the ability to augment castings and forgings
	Material Performance		Characteristics of material produced via AM that can have an impact on end-part performance
		Property Variation	Inconsistency in material properties from a consistent value, including relative to that of traditionally produced components
		Surface Finish	Roughness of the external surface of a printed part, including its impacts on fatigue strength
		Porosity	Unintentional voids within a printed component due to errors/undesired behavior during printing
		Data	Information collected on material characteristics that collectively define performance
	Business Constraints		Non-technical barriers that prevent the adoption of AM by casters and forgers
		Economics	The cost of AM machinery, material, or support services are significant and present a barrier to adoption
		Workforce Education	Insufficient knowledge of AM capabilities to assist with the development of AM solutions presents a barrier to adoption
		Decision Tools	Considerations to help determine when to use AM and which AM technology to use
		Regulations	Restrictions that impact the use of AM, such as powder sourcing and storage
	Post-Processing		Process steps following the initial additive manufacturing to finish a part
		Machining	Removal of material to achieve appropriate surface finish and tolerances
		Thermal Processing	Post-processing steps to achieve appropriate microstructure/mechanical properties
		Burn Out	The process associated with removing a 3D printed pattern from a shell or the ability to remove binders from sand molds
	Industry Maturity		The relative newness of the technology that impacts the proliferation of its use
		Intellectual Property	Lack of insight into processing parameters and material information
		Limited OEM Printers	Limited market for a specific type of printer

L1 Code	L2 Code	L3 Code	Definition
		Material Sourcing Flexibility	OEM printers that require that their materials be used in their machines
		Confidence in AM	Overall concern about additive manufacturing capabilities and reliability due to the relative newness of the technology
	Technology Limitations		AM technology may not be mature enough to control process parameters to match the capabilities of traditional casting and forging processes
		Material Availability	Materials available through traditional production methods may not be available for AM processes (includes alloys, powders, waxes, and multi-material printing tech)
		Build Volume	The build volume for the majority of AM technologies is not large enough to handle the cast or forged part or tooling for that part
		In-situ measurements	The hardware and infrastructure to support in-situ measurements (data processing and measurement) may not be in place
		Tolerances	Today's AM technology may not be capable of hitting the tight tolerances compared to traditional methods
		Computational Modeling	Computational modeling and simulation methods for AM processes may not be as mature as similar tools available for traditional casting and forging processes
	AM Qualification		Testing and proving the suitability of a component, process, or material for a particular use
		Standards/ Specs	Testing methodologies and requirements against which to assess performance
		NDT	Methods that assess a part's geometry or internal volume without needing to test to failure or section the part
		Material Qualification	Approving a material for certain uses by demonstrating certain processing creates material that meets a comprehensive set of acceptance criteria

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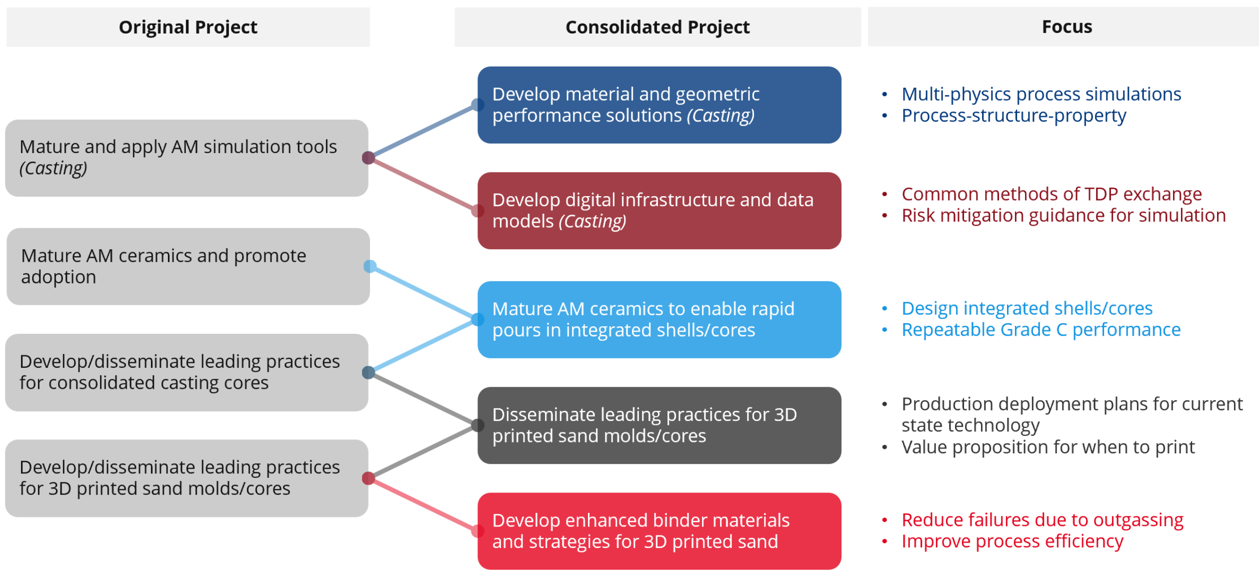
Appendix I- Project Consolidation

Based on the execution plans defined in the Functional Analysis Workshops, the following projects were modified to retain a dedicated focus for each:



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