Casting & Forging Digital Fabric Roadmap

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Prepared by MxD | Version 1.0 | June 2026

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Acknowledgments

MxD extends gratitude to our partners in this project, as well as industry stakeholders, trade associations, workforce organizations, academic and government partners. Your invaluable insights to advance the Casting & Forging (C&F) industry have been instrumental in supporting the future of Casting & Forging for the Defense Industrial Base (DIB). We would also like to formally acknowledge our sponsors, the U.S. Department of War's (DOW) Office of the Secretary of Defense (OSD) Industrial Base Analysis and Sustainment Program (DOW-IBAS) and the Manufacturing Technology Program (OSD-ManTech), whose support has been vital to this initiative. Additionally, we recognize the contributions of the project team, formal contributors, and reviewers. The specific outputs—including work domains, roles taxonomy, role success profiles, and other assets—have undergone rigorous peer review by various combinations of these contributors.

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

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Executive Summary

The casting and forging (C&F) industry—an essential pillar of the United States Defense Industrial Base (DIB)—is at a pivotal moment as technological capabilities advance and global market demands intensify. C&F components form the backbone of military platforms, critical infrastructure, and advanced defense systems, making the industry indispensable to national security. However, the industry faces mounting pressure from decades of offshoring, an aging asset base, workforce shortages, and insufficient modernization investments.

There is variation in government and trade association estimates, but our best estimate is that the number of U.S. foundries and forge shops has declined by roughly 40 percent since 2000, underscoring a sustained erosion of domestic industrial capacity and the urgency of coordinated revitalization efforts.[1]

To address these challenges, MxD and its partners developed a digital fabric roadmap that outlines how digital manufacturing technologies can strengthen the resilience, competitiveness, and long-term viability of the C&F industry. This roadmap highlights the transformative impact of digital tools across design, production, quality assurance, and supply chain management, and defines a portfolio of projects to accelerate adoption of advanced solutions.

Through extensive research and collaborative workshops, the team identified key operational and technological gaps constraining the C&F industry. By mapping these gaps to targeted digital enablers, the roadmap outlines a clear path for advancing state-of-the-art C&F capabilities. The result is a modernization framework designed to strengthen the resilience, productivity, and digital readiness of the DIB and enhancing the ability to meet future defense requirements with a more agile, innovative, and secure supply chain.

Over four months, MxD and its partners conducted a research effort spanning more than 100 industry reports, 65 data sources, three multi-stakeholder workshops, and over 25 interviews. This process engaged 60 stakeholders across government, primes, small suppliers, trade associations, and academia to validate problem statements, uncover root causes, and shape feasible digital interventions. The resulting C&F Digital Fabric Roadmap translates these insights into 24 implementable projects aligned to four strategic workstreams. Each project is sequenced across a five-year horizon and addresses specific capability gaps—from sensor retrofits and digital twins to model-based procurement, workforce upskilling, and supply chain transparency—forming a practical blueprint for accelerating digital adoption and strengthening the DIB.

[1] U.S. Department of Energy, *Market Research on the U.S. Metal Casting Industry*, 18.

Overview

The Casting & Forging Digital Fabric Roadmap is a five-year strategy (FY26–FY30) defining how digital manufacturing technologies can help modernize the Casting & Forging (C&F) industry. The purpose is to align the C&F ecosystem around a unified blueprint that addresses today's challenges, which includes aging equipment, workforce gaps and supply chain vulnerabilities, and lay out a clear path of initiatives to improve readiness, productivity, precision, and resilience. Overall, the C&F roadmap translates current challenges into prioritized digitally enabled projects and investments that will accelerate modernization and bolster defense readiness.

Approach and Methodology

The development of the C&F Digital Fabric Roadmap follows a structured, multi-phase methodology grounded in research, stakeholder engagement, and validation. The process spanned four months and was anchored by a series of workshops hosted at the MxD facility in Chicago, Illinois.

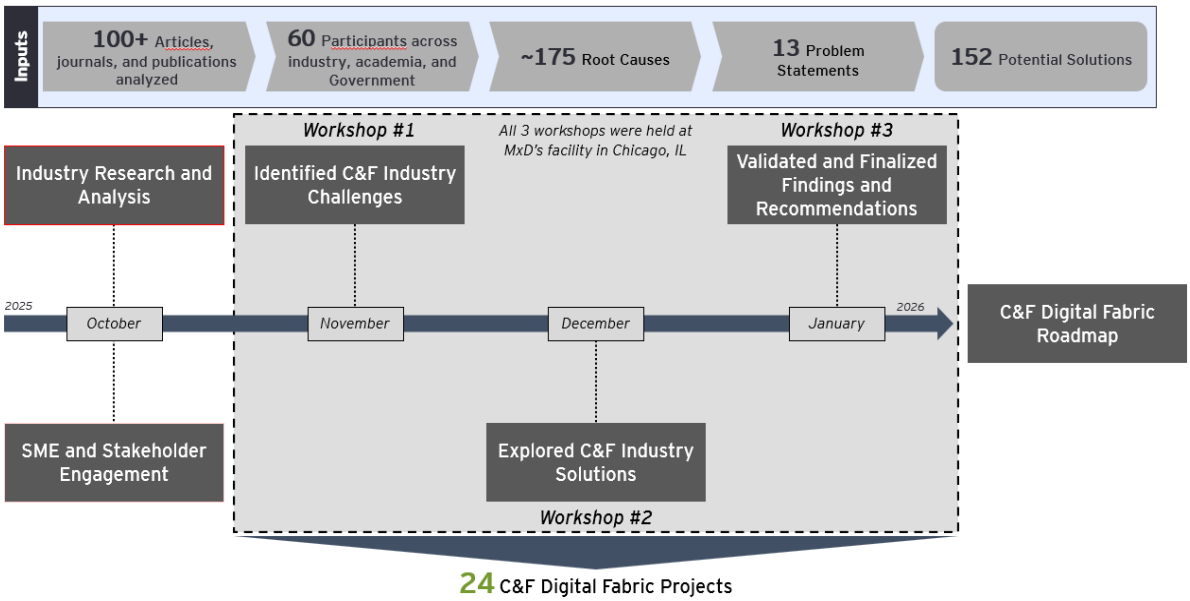


Figure 1. *C&F Digital Fabric Roadmap Development Approach*

As illustrated in Figure 1, the roadmap was built on a foundation of inputs:

- The team reviewed over 100 articles, journals, and publications to identify trends, gaps, and best practices in digital manufacturing.
- 60 participants from industry, academia, and government/DOW contributed insights.
- The team synthesized approximately 175 root causes into 13 core problem statements, which informed the ideation of 152 potential solutions.

These workshops were supported by ongoing industry research and analysis, as well as subject matter resources and stakeholder engagement.

The Roadmap

The Casting & Forging Digital Fabric Roadmap is organized into four strategic workstreams that address four dimensions of digital modernization goals for the C&F industry:

- **Smart Factory and Automation:** High-quality data will improve the accuracy and impact of analytics, digital twins, and predictive maintenance to modernize legacy operations.
- **Workforce and Talent**: Immersive, digital-first training will create engaging, motivating pathways to expose and prepare a future-ready C&F workforce.
- **Supply Chain and Production**: Strategic assessments and digital tools will strengthen visibility and resilience across critical material supply chains.
- **Standards and Compliance**: Digital standards and centralized platforms aim to streamline procurement and reduce compliance complexity.

The roadmap builds on feedback from engaged C&F stakeholders who identified critical insight into systemic barriers impacting day-to-day operations. This report maps potential digital strategies and technologies to address each challenge and prioritizes high-impact projects to tackle the identified challenges.

This portfolio of 24 scalable, actionable initiatives deliver measurable outcomes and supports the broader mission of enhancing defense manufacturing agility, capacity and long-term resilience. Adoption of this roadmap will establish a structured framework for modernizing the C&F industry, promoting standardization and accelerating digital transformation.

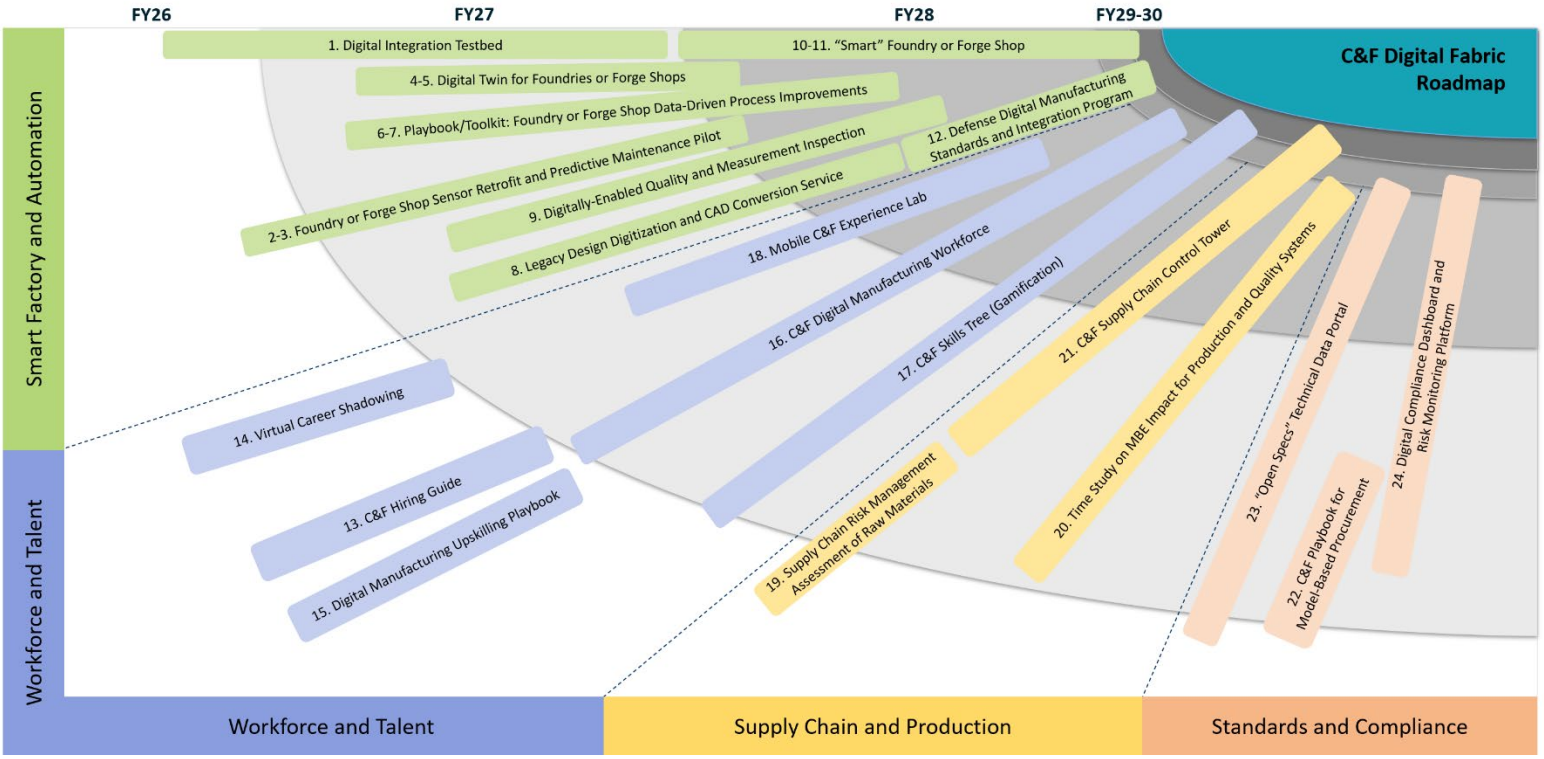


Figure 2. *U.S. C&F Digital Transformation Roadmap, FY26–FY30*

24 Actionable Projects: The Next Steps for C&F Modernization

Smart Factory & Automation

1. **Digital Integration Testbed –** A modular testbed that allows C&F manufacturers to safely test, benchmark, and validate digital technologies before full production deployment
2. **Foundry Sensor Retrofit and Predictive Maintenance Pilot –** A pilot program that retrofits legacy foundry equipment with sensors to enable predictive maintenance and reduce unplanned downtime
3. **Forge Shop Sensor Retrofit and Predictive Maintenance Pilot –** A pilot program that retrofits legacy forge shop equipment with sensors to enable predictive maintenance and reduce unplanned downtime
4. **Digital Twin for Foundries –** A real-time digital twin that uses standardized shop-floor data to optimize foundry processes, maintenance, and workforce decision-making
5. **Digital Twin for Forge Shops –** A real-time digital twin that uses standardized shop-floor data to optimize forge shop processes, maintenance, and workforce decision-making
6. **Playbook/Toolkit: Foundry Data-Driven Process Improvements –** A practical playbook/toolkit that helps small and mid-sized foundries apply data and digital solutions to improve quality, efficiency, and energy performance
7. **Playbook/Toolkit: Forge Shop Data-Driven Process Improvements –** A practical playbook/toolkit that helps small and mid-sized forge shops apply data and digital solutions to improve quality, efficiency, and energy performance
8. **Legacy Design Digitization and CAD Conversion Service –** A secure service that converts legacy 2D drawings into validated, standards-compliant 3D CAD models to enable modern digital workflows
9. **Digitally-Enabled Quality and Measurement Inspection –** A phased initiative that uses advanced analytics to improve inspection accuracy, reduce scrap, and optimize C&F production processes
10. **"Smart" Foundry –** A pilot smart production line that applies sensors and analytics to legacy foundry equipment to improve uptime, quality, and scalability
11. **"Smart" Forge Shop –** A pilot smart production line that applies sensors and analytics to legacy forge shop equipment to improve uptime, quality, and scalability
12. **Defense Digital Manufacturing Standards and Integration Program –** A DOW-led program that standardizes and validates machine-readable digital design data to enable interoperable, model-based manufacturing across the C&F industrial base

Workforce & Talent

13. **C&F Hiring Guide –** A targeted hiring and workforce-planning guide that helps C&F employers attract, onboard, and retain talent aligned to industry demand and regional pipelines
14. **Virtual Career Shadowing –** A short, on-demand digital experience that introduces students to modern C&F careers through real-world storytelling
15. **Digital Manufacturing Upskilling Playbook –** A playbook that guides C&F manufacturers on adoption of digital technologies in a systemic way and upskill their workforce using proven methods
16. **C&F Digital Manufacturing Workforce –** A modular, credentialed training platform that combines digital skills instruction to prepare a future-ready workforce
17. **Skills Tree (Gamification) –** An interactive, gamified career-pathway platform that links C&F skills, training, and credentials to real hiring and advancement opportunities

18. **Mobile C&F Experience Lab –** A mobile, hands-on outreach lab that showcases modern C&F technologies to students, educators, and communities to spark early career interest

Supply Chain & Production

19. **Supply Chain Risk Management Assessment of Raw Materials –** A strategic assessment that identifies raw-material supply risks, alternative sourcing options, and mitigation strategies critical to C&F and defense readiness
20. **Time Study on MBE Impact for Production and Quality Systems –** A data-driven study that quantifies how Model-Based Engineering improves qualification time, throughput, and quality in C&F operations
21. **C&F Supply Chain Control Tower –** A digital marketplace and forecasting platform that connects DOW demand signals to pre-certified C&F suppliers, improving planning and resilience

Standards & Compliance

22. **C&F Playbook for Model-Based Procurement –** A standards-alignment playbook that enables consistent use of model-based design and reduces NRE costs in C&F procurement
23. **"Open Specs" Technical Data Portal –** A secure, centralized portal that provides a single source of truth for DOW technical data, standards, and solicitation clarifications
24. **Digital Compliance Dashboard and Risk Monitoring Platform –** A centralized compliance platform that automates tracking, reduces reporting burden, and improves audit readiness for C&F manufacturers

Roadmap – Projects Timeline

The roadmap conveys its meaning most effectively through a visual layout with a detailed structure of individual projects. Figure 2 below provides a snapshot of the full roadmap, illustrating project sequencing across FY26–FY30:

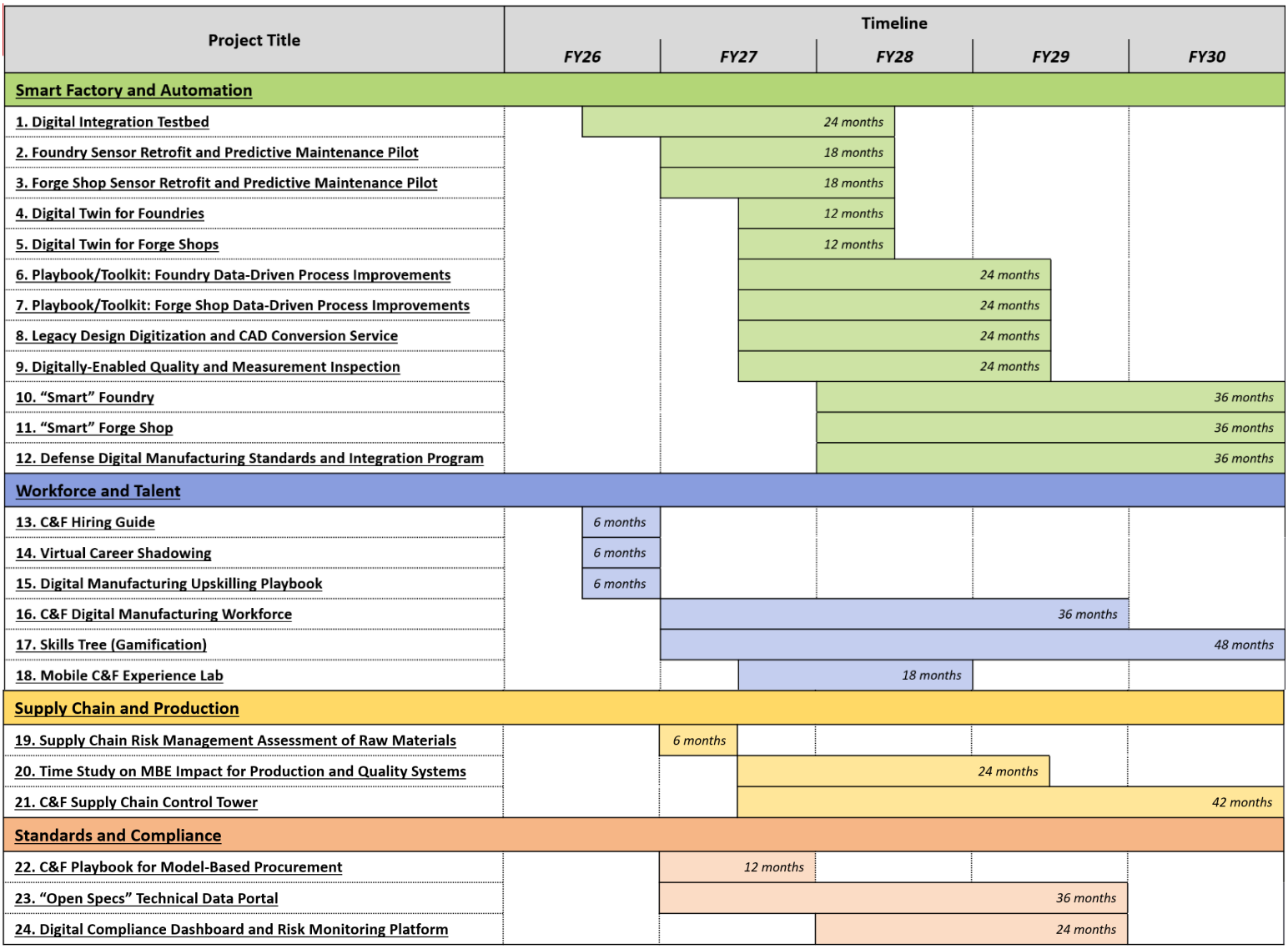


Figure 3. *Roadmap Project Structure*

A consistent set of attributes defines each project within the roadmap, promoting clarity, alignment, and execution readiness:

- **Project Title**: A concise name that captures the project's focus.
- **Timeline**: The expected launch and duration, expressed in months, mapped across fiscal years.
- **Outcome**: A brief statement of the intended result or benefit.

Each project is actionable and aligns with the strategic goals of the roadmap. Some projects build upon one another, with early pilots and assessments that form the foundation for more complex implementation in subsequent years.

To view full project attributes for each of the 24 projects, visit Appendix A.

Next Steps: Path Forward

The next phase of the C&F Digital Fabric Roadmap focuses on execution. Priority projects with high readiness and impact should begin in FY26, starting with workforce development, foundational assessments, and pilot deployments. Project leadership must establish a governance structure to oversee implementation, track progress, and confirm alignment with the U.S. Department of War's strategic goals.

Early project outcomes will establish the foundation for future projects. Sharing results and lessons learned will be critical to drive momentum and encourage broader industry participation. Sustained commitment across stakeholders will be essential to deliver measurable impact.

Background and Approach

Roadmap Structure

One of the central priorities of the Industrial Base Analysis and Sustainment (IBAS) program—an Office of the Secretary of Defense (OSD) initiative focused on addressing critical risks and strengthening the DIB—is to ensure the domestic capability and capacity for cast and forged components. This includes both improving the performance and resilience of existing suppliers and advancing alternative manufacturing approaches for specialty metal alloys, which are essential to defense systems across air, land, sea, and space domains.

MxD, the Manufacturing Innovation Institute (MII) for Digital Manufacturing and its partners developed this initiative through extensive research and a series of collaborative workshops with government, industry, academia, and trade associates. Building on prior modernization efforts led by America Makes (Additive Manufacturing) and ARM (Robotic Manufacturing), this effort advances a unified C&F modernization strategy.

By identifying operational and technological gaps across the C&F ecosystem and aligning them with targeted digital enablers, the resulting roadmap provides a clear path to modernizing C&F capabilities. The overarching objective of the roadmap is to accelerate DIB modernization to meet future defense needs through a more resilient, innovative, and digitally enabled supply chain.

Objectives

- Establish a cohesive digital modernization roadmap for the U.S. C&F industry.
- Identify and quantify critical industry pain points and capacity constraints impacting defense readiness.
- Engage industry, government, and academia to build a shared understanding and alignment.
- Translate current-state challenges into root causes to guide targeted modernization efforts.
- Develop actionable digital manufacturing solutions that enhance productivity, quality, and resilience.
- Strengthen the DIB through improved C&F technological capabilities and collaboration.
- Benchmark leading practices and relevant technologies to inform future-state recommendations.
- Prioritize high-impact initiatives and investment pathways that accelerate adoption.

Figure 4. *Digital Fabric Roadmap Project Objectives*

Industry Context and Strategic Imperative

The C&F industry plays a critical role in supporting the DIB, supplying mission critical components essential for military platforms, advanced weapons systems, and national infrastructure. However, the industry stands at a defining crossroads. As internal industry analyses and roadmap materials highlight, trends such as sustained offshoring, aging equipment, and inconsistent modernization investments are driving this decline.

Key Market Trends Shaping the Casting and Forging Landscape

The metal casting market was $54.9 billion in 2024 and projected to grow to $85.6 billion by 2034, reflecting strong demand and renewed modernization across major industries. The aerospace and defense sector accounted for 45.6% of global casting revenue in 2024, underscoring the sector's importance to national security and advanced manufacturing.

The metal forging market shows similar momentum, with forecasts estimating growth to $21.3 billion by 2030, an annual rate of 7.6%. This rise reflects increasing demand for high-strength, mission-critical components.

Together, these trends highlight both the scale of the opportunity and the strategic need to strengthen casting and forging capabilities to meet future defense and commercial requirements.

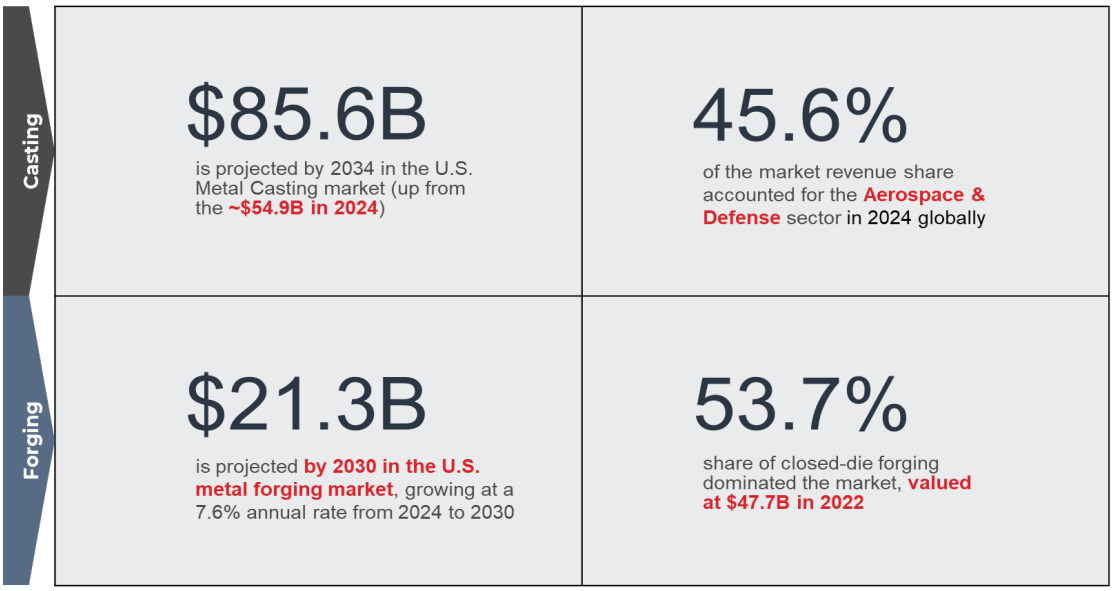


Figure 5. *Market Snapshot: U.S. C&F and A&D Segment Share*

As of 2024, the total estimated U.S. revenue for the metal casting and forging industries was approximately *$64–66 billion*, consisting of roughly *$50–55 billion* from metal casting and *$10–14 billion* from forging.[2] [3] [4]

Rapid global market shifts and advancing technologies require the U.S. C&F industry to adapt and innovate. Addressing workforce shortages, supply chain disruptions, and rising international competition is essential to meet projected increase in demand. By modernizing processes and adopting new digital technologies, the industry can strengthen its resilience and competitiveness, ensuring it remains a critical foundation of the DIB.

These trends, combined with structural pressures, surfaced several core challenges across four modernization dimensions.

Key themes and challenges distilled from research review and Workshop 1

Smart Factory and Automation	Supply Chain and Production	Standards and Compliance	Workforce and Talent
Low tech adoption	Tier 2/3 supplier gaps	Non-standardized DOW requirements	Aging labor force
Aging equipment & limited automation	Volatile pricing	High compliance burden	Training & skills gaps
Legacy systems blocking digitization	Long lead times	Difficult qualification of AM-enabled parts	Talent mismatch
Insufficient data infrastructure	Material shortages	Bureaucratic inertia	Lack of manufacturing awareness-
Slow qualification of new digital/AM processes	Complex DOW procurement barriers and lack of demand	Lack of industry standards for digital/AM tooling	Attrition due to low pay & limited career growth

[2] Business Research Insights, *Forging Market Size & Industry Analysis [2035], CAGR of 5.2%*
[3] Mobility Foresights, *USA Foundry and Casting Market Size and Forecasts 2031*
[4] Market Research Future, *US Metal Forging Market Size | Industry Report 2035*

About the Authors

This report presents the results of a formal effort to assess the current state and prospects of the C&F industry. Recognizing the industry's critical importance, the authors synthesized insights from industry, government, and academia to provide a focused analysis of challenges and opportunities. This effort delivers a digital roadmap to guide industry's advancement and resilience in a rapidly changing environment.

Organization	Role/Expertise
MxD (Manufacturing x Digital)	MxD (Manufacturing x Digital) strengthens, modernizes and secures U.S. manufacturing through technology innovation, workforce development, and cybersecurity preparedness. In partnership with the U.S. Department of War (DOW), MxD convenes the industrial base to solve critical manufacturing challenges by accelerating digital adoption, empowering a skilled workforce, and modernizing supply chains. MxD is also the DOW-designated Digital Manufacturing & Cybersecurity Institute.

Methodology and Approach

Approach

The *Castings & Forgings Digital Fabric Roadmap* was developed over four months, from October 2025 to February 2026. The approach balances analytical rigor with sustained stakeholder engagement to generate well-grounded, practical insights.

The project centered on three structured workshops, sequenced to advance the work from challenge identification to solution development, to a clear path forward. Each workshop built on the last, with targeted synthesis between sessions to refine findings and guide subsequent discussions. The team worked closely with stakeholders to validate insights, maintain alignment, and ensure continuity across phases.

By combining workshop insights with research and report reviews, the team developed a prioritized set of initiatives that form the foundation of the digital roadmap. The framework below shows how these workshops moved the effort from exploration and problem identification to solution design, planning, and implementation.

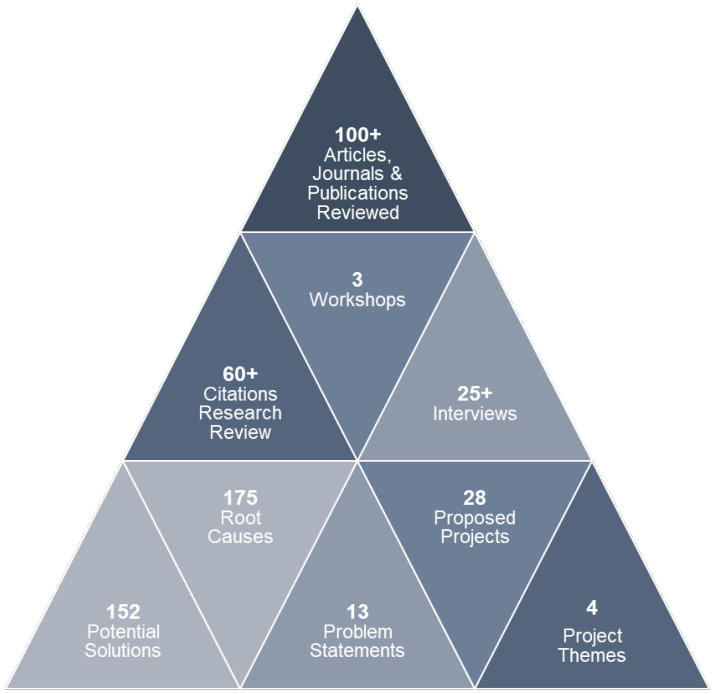


Figure 6. *Roadmap Collaboration Methodology*

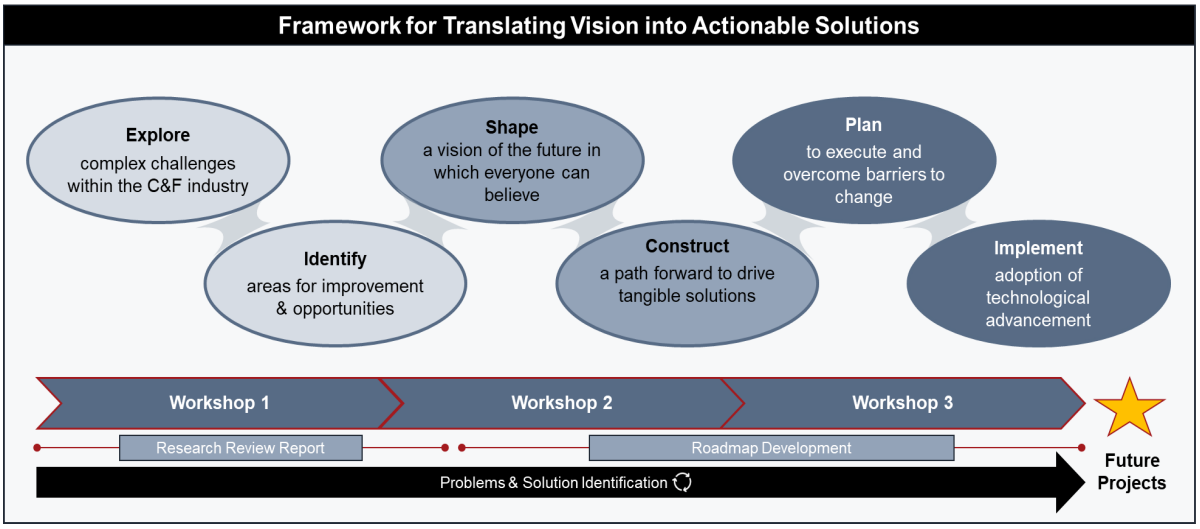


Figure 7. *Roadmap Collaboration Methodology*

Assumptions and Constraints

The approach was based on several key assumptions, including:

- Workshop feedback reflected broader industry perspectives.
- Publicly available and internal data sources were sufficiently current and accurate to inform analysis.
- Participants possessed the requisite subject matter expertise to validate problem statements and assess proposed solutions.
- Projects would benefit both the DOW and industry partners.
- Key constraints included limited time, variable data maturity across sources, and dependency on subject matter resources.

Rationale for the Approach

The team chose this approach to combine analytical depth with extensive stakeholder engagement—essential in an industry defined by complex processes and diverse capabilities. The team combined literature review with a series of workshops to reflect both technological trends and real-world implementation constraints in the roadmap. The approach enables understanding of the current state, identification of key challenges, determination of root causes, and development of practical solutions. The framework below illustrates the progression from gathering inputs and context, to generating insights, defining initiatives, and producing a digital roadmap.

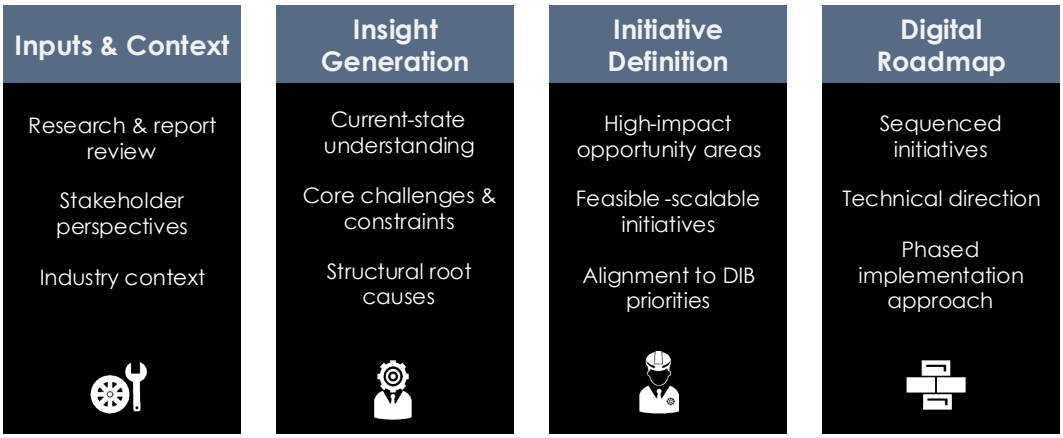


Figure 8. *Framework for Generating Insights and Defining the Digital Roadmap*

Research Overview

Research Approach

The team began by forming a hypothesis based on early stakeholder interviews and prior C&F studies, which shaped the key questions for assessing the current state of the DIB. Building on this foundation, the team conducted a structured review of articles, journals, publications, and market data, analyzing operational pain points and previous C&F assessments.

Insights from Workshop 1—where industry, government, and academic participants validated trends and root causes—were then integrated to ground the research in real operational experience. Synthesizing these inputs produced a comprehensive, evidence-based view of the pressures shaping the C&F ecosystem and the systemic factors limiting capacity, supply chain performance, technology adoption, and workforce resilience. These findings formed the basis for targeted interventions and the digital modernization roadmap.

Research Approach

The team executed a comprehensive research effort that combined academic literature, industry journals, federal and defense analyses, market data, workforce studies, technology roadmaps, and prior MxD project outcomes. Insights from the MxD Workshop further strengthened this analysis.

This rigorous process validated industry pain points, benchmarked global and industry trends, revealed systemic root causes, and triangulated findings across authoritative sources to build a holistic, evidence-based understanding of the C&F ecosystem. In total, the report referenced 65 unique sources, providing a robust analytical foundation for the roadmap's recommendations. Appendix B summarizes the key topic areas evaluated in the review.

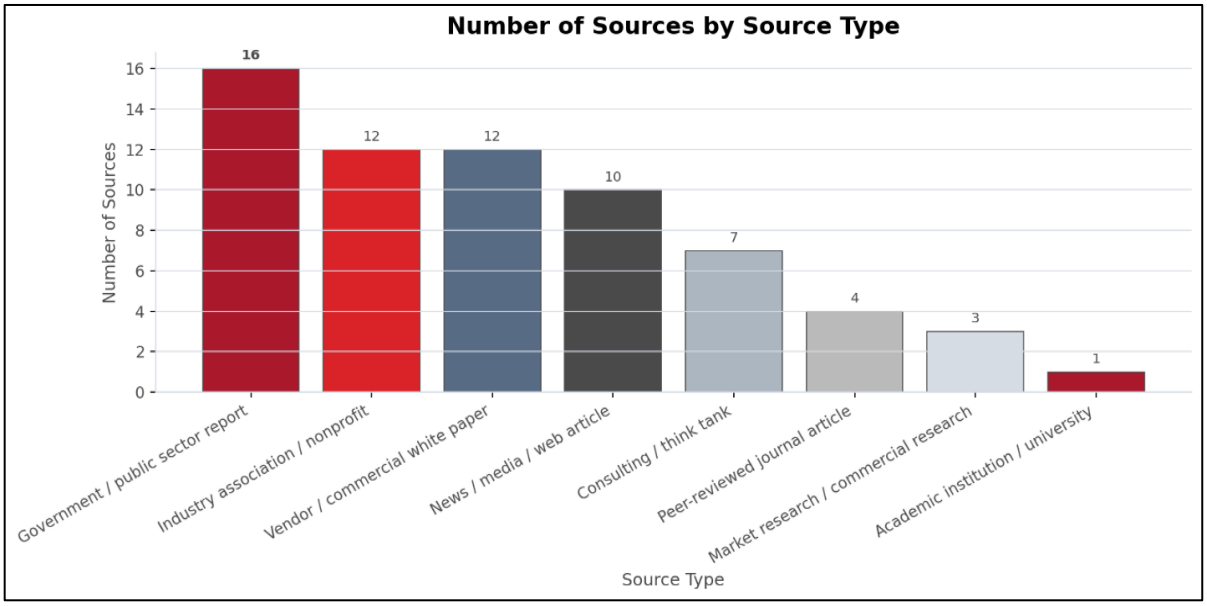


Figure 9. *Distribution of Research Sources by Type*

Research Guiding Steps

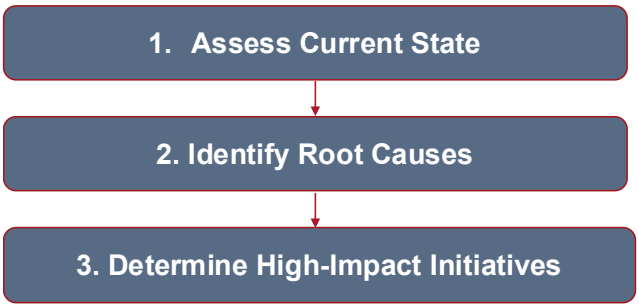


Figure 10. *Research Guiding Steps*

To structure the analysis and confirm that findings directly supported actionable recommendations, the team centered the study on three guiding research questions. These questions assessed the current state of the C&F ecosystem, identified the root causes of systemic challenges, and determined which interventions would generate the greatest impact. They provided a disciplined framework for evaluating digital modernization opportunities across the DIB and pinpointed the digital tools, technologies, and process improvements with the highest potential to modernize, stabilize, and expand production capacity. Together, the questions created an end-to-end methodology linking ecosystem diagnosis to evidence-based modernization strategies.

Key Areas of Research

The research team used a three-level analytical framework to ensure consistency, clarity, and traceability from high-level strategic themes down to specific, research-validated challenges. This structure supports both executive-level insight and detailed issue identification.

At the highest level, Pillars represent the major strategic domains used to assess industry performance and readiness. Each Pillar contains Focus Areas, which group related challenges within that domain. Key Issues then capture the specific, observable problems identified through research, data analysis, and stakeholder input. This hierarchy ensures that individual issues align clearly with broader strategic constraints, supporting effective prioritization and targeted research. Figure 11 below depicts application of Pillars, Focus Areas, and Key Issues in the analysis.

PILLAR	High-level strategic domain defining major area of evaluation **Ex:** Capacity, Supply Chain, Technology, Workforce
FOCUS AREA	Category within the pillar that groups related issues **Ex:** *Infrastructure Limitations, Demand Alignment*
KEY ISSUES	Specific, research-validated problems observed within the focus area **Ex:** *Inconsistent Demand Signals, Long Lead-Times, Workforce Skill Gaps*

Figure 11. *Structure of Evaluation Domains*

Appendix B provides an extract from the research review conducted across the four key Pillars. Using this framework, the team examined each Pillar as a critical dimension in answering the core research questions.

Using the framework described above, the team conducted research across four core Pillars. Each Pillar represents a critical dimension that was studied in answering the core questions in the associated research categories.

1. **Capacity:** The industry's ability to meet both current and future demand considering infrastructure limitations, capital investment constraints, and persistent production bottlenecks.
2. **Supply Chain:** Visibility and vulnerabilities across fragmented supplier networks, including challenges related to material availability, extended lead times, and overall supply chain resilience.
3. **Technology:** The industry**'s** readiness to adopt modern digital tools, data management practices, automation, simulation capabilities, and cybersecurity measures.
4. **Workforce:** Labor shortages, skills gaps, training pipelines, and cultural barriers that affected talent attraction, development, and long-term retention.

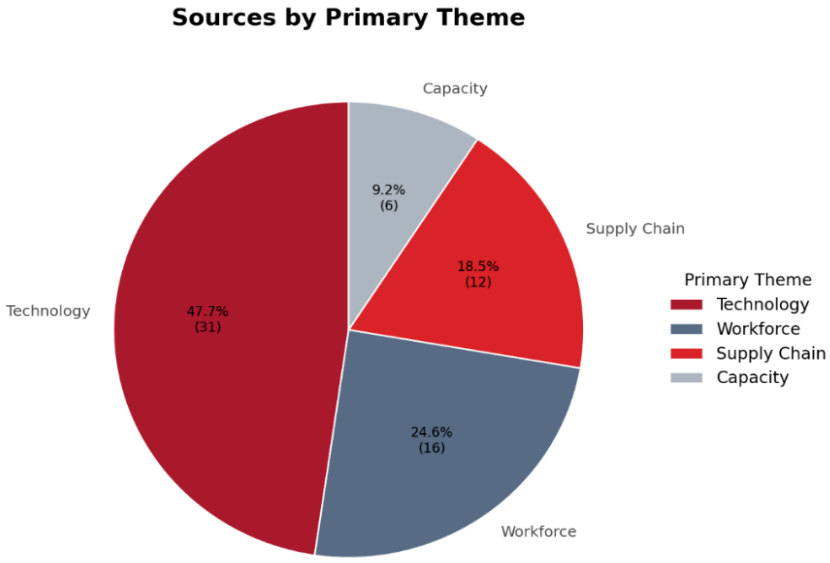


Figure 12. *Distribution of Sources by Primary Theme*

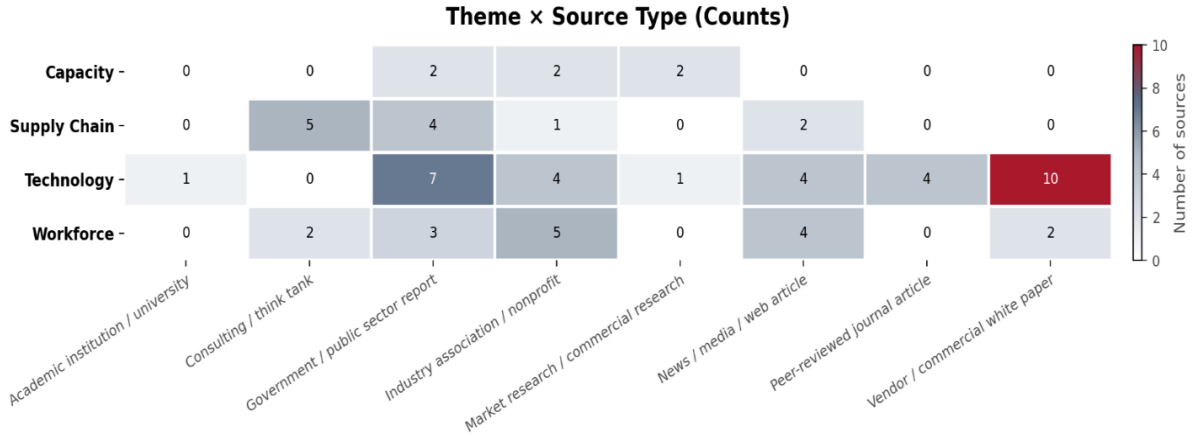


Figure 13. *Theme Breakdown by Sources*

Current State Analysis – C&F Landscape Under Strain

The C&F industry is navigating a complex landscape: while it appears to have robust capacity on paper, much of that capacity is underused, understaffed, outdated, and not suited to current defense and commercial needs. Since 2000, the industry has lost more than 240 forging plants, along with tens of thousands of skilled jobs, weakening domestic capabilities. Remaining facilities often rely on decades-old equipment, maintain inefficient layouts, and struggle with frequent maintenance problems that reduce productivity.

In parallel with these setbacks, many foundries or forge shops face additional challenges that prevent them from running at full capacity. Utilization rates can be as low as 50% in some areas, due to unpredictable demand, especially for specialized, small-batch defense contracts. Such fluctuations make steady investment in new equipment or staff risky. This leads to a common misconception that physical capacity in the U.S. falls short, when in fact issues with demand alignment and qualification barriers prevent full utilization of existing resources.

Supply chain fragmentation adds another challenge. Most Original Equipment Manufacturers (OEMs) only closely monitor their direct suppliers (Tier-1), so visibility into second- and third-tier suppliers is limited. This is particularly problematic for DOW, where traceability and compliance are critical. Inconsistent documentation and legacy data contribute to delays and quality variation. Additionally, the industry relies heavily on imported critical minerals like nickel, cobalt, titanium, and magnesium, increasing exposure to global disruptions—just as defense needs are growing.

Technology adoption is inconsistent across the industry. Many foundries and forges operate in difficult environments that hinder the use of sensors and modern controls, further complicated by upgrades to older machinery. Additionally, resistance to change, along with gaps in cybersecurity and technical skills, slow progress toward digital transformation. Advanced tools like digital twins exist but see limited use due to inadequate data infrastructure and technical documentation.

Workforce challenges further threaten the future of the industry. Nearly a quarter of manufacturing workers are over 54 and contemplating retirement. Younger generations are often reluctant to pursue careers in demanding, inflexible settings that lack remote work options. Skill shortages–especially in data, robotics, diagnostics, and digital technologies—create additional obstacles for industry to modernize, even when new equipment is available.

Synthesis of Findings and Strategic Implications for Digital Modernization

Building on the current state analysis and the four-dimensional assessment across capacity, supply chain, technology, and workforce, the research reveals a set of insights that define the structural realities of the C&F ecosystem. These insights synthesize evidence from the literature review, data analysis, and MxD workshop discussions, and they establish the critical conditions that must be addressed to enable sustainable digital modernization within the DIB.

Capacity

Domestic C&F capacity remains significantly underutilized due to volatile demand signals, short-term contracting, and uncertainty that discourages capital investment. Aging facilities, equipment bottlenecks, and high compliance and operating costs further restrict throughput and scalability. Although physical capacity exists, misalignment between procurement practices and industrial economics prevents rapid or sustained production increases. This disconnects limits responsiveness to defense needs and increases reliance on foreign suppliers during demand surges.

Supply Chain

The C&F supply chain faces escalating risk due to structural fragmentation, limited multi-tier visibility, and increasing reliance on foreign sources, particularly within the DIB. OEMs' limited insight beyond Tier 1 suppliers, combined with inconsistent quality standards and weak digital traceability, obscures critical vulnerabilities and constrains supplier flexibility. Material and labor shortages, volatile DOW demand, and minimal surge capacity contribute to extended lead times – often exceeding 18 months – further straining responsiveness. Together, these conditions result in a supply chain that is difficult to scale, slow to recover, and strategically exposed, reinforcing the urgency for coordinated action to strengthen transparency and domestic resilience.

Technology

Slow adoption of advanced manufacturing technologies continues to limit productivity, quality, and resilience across casting and forging operations. Legacy equipment, outdated technical data, and incompatible digital systems constrain integration, while high implementation costs, workforce skill gaps, and cybersecurity requirements slow modernization. Limited use of simulation and digital twins forces reliance on trial-and-error production, increasing cost and lead times. As a result, technology fragmentation remains a core barrier to meeting modern defense and industrial requirements.

Workforce

Skilled labor shortages and accelerating retirements are constraining output and threatening the loss of

critical institutional knowledge. Physically demanding work environments, negative perceptions of manufacturing careers, and competition from other industries hinder recruitment, while limited training and apprenticeship pipelines slow replacement and upskilling. Gaps in digital and advanced manufacturing skills further impede modernization efforts. Without intervention, workforce constraints will continue to cap capacity, delay technology adoption, and weaken long-term industry resilience.

Synthesis of Findings and Strategic Implications for Digital Modernization

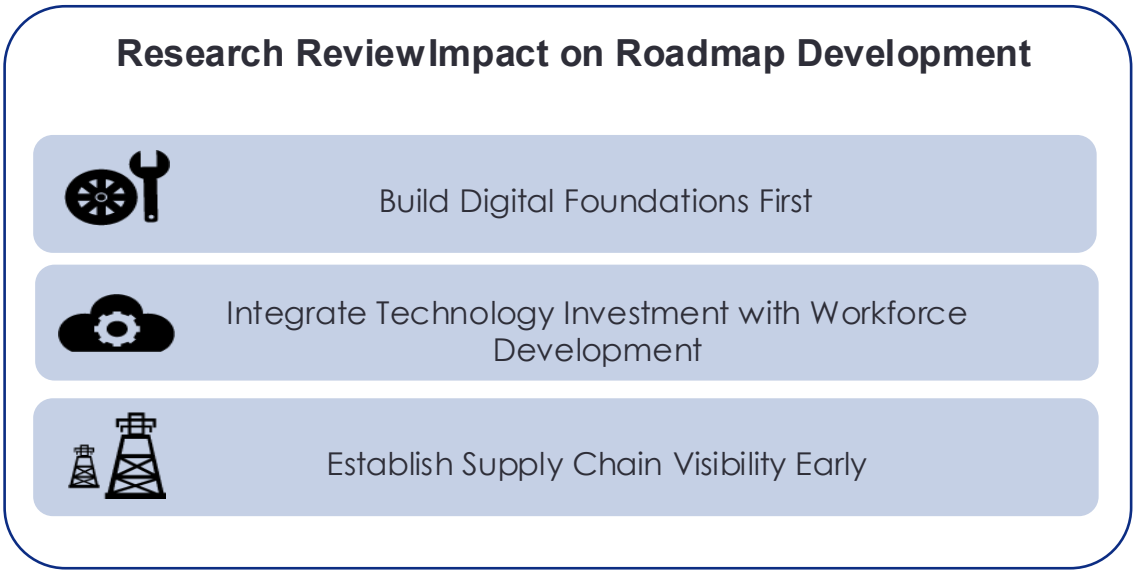


Figure 14. *Research-Driven Priorities Shaping the Roadmap*

Engagement (Workshops & Interviews)

Stakeholder Involvement Overview

To develop a robust and relevant roadmap for the C&F industry, MxD and its partners conducted three workshops. The team designed these sessions to actively engage a broad spectrum of stakeholders, including industry leaders, academic experts, and government representatives—to gather diverse perspectives, build consensus, and develop a prioritized dialogue.

Across the three workshops, MxD and its partners engaged 60 unique stakeholders, generating 86 total workshop participations. Attendance remained strong throughout the series—with 33 participants in Workshop 1 ("Defining the Current State of C&F"), 31 in Workshop 2 ("Understanding Potential Solutions to Advance Casting & Forging through Digital Manufacturing"), and 22 in Workshop 3 ("Validating Input for the Digital Manufacturing Roadmap for U.S. Casting & Forging"). This progression not only demonstrates sustained stakeholder commitment but also highlights the evolving mix of participants who contributed fresh insights, challenged assumptions, and helped refine the roadmap at each stage of development. Appendix F2 depicts the breakdown of workshop participants by category.

Total Participation Across Workshops

Workshop 1	Workshop 2	Workshop 3
33	31	22

Figure 15. *Total Participants by Workshop*

The intake process also included interviews featuring targeted questions tailored to each stakeholder's expertise and role. This methodology allowed for the collection of specific feedback and validation of initiatives, aligning the digital roadmap with real-world needs and leveraging broad expertise across the C&F industry.

To further complement the workshop insights and strengthen the overall rigor of the engagement process, the team conducted approximately 25 interviews over the course of the project. These included internal SMEs from both MxD and its partners who provided ongoing guidance, as well as external stakeholders representing key segments of the ecosystem. Notably, a focused set of 10 interviews conducted between Workshops 1 and 2 gathered additional feedback on workshop execution and further explored critical challenges surfaced during the initial session.

Interviews Conducted

Workshop Participants	Partner SMEs	MxD SMEs
10	10	5

Figure 16. *Post-Workshop SME Interviews*

Stakeholder Involvement

From a broader perspective, workshop participants represented three primary stakeholder categories: government, academia, and industry. Engaging industry leaders, trade associations, academia, government entities, and small- and medium-sized businesses (SMBs) helped to ground the roadmap in real-world manufacturing constraints, informed by cutting-edge research, aligned with workforce development and regional economic priorities, and supported by practical implementation pathways shaped by equipment providers, technology developers, and public-sector stakeholders. To further strengthen this perspective, stakeholder engagement included startup founders and venture capital representatives whose innovation-driven viewpoints align with the Pentagon's current emphasis on engaging nontraditional partners to accelerate technology transition and manufacturing modernization. This balanced representation enabled the consideration of both near-term operational realities and longer-term innovation objectives across the C&F ecosystem. Appendix F1 presents a detailed summary of the stakeholders who participated in the workshops, and Appendix F2 provides a breakdown by specific companies and organizations that were a part of the roadmap creation.

Affiliation	Perspective
Industry	Grounded the roadmap in operational reality by anchoring priorities in current manufacturing conditions. This perspective emphasized production constraints, workforce availability, legacy equipment challenges, supply chain fragility, and cost competitiveness, reinforcing that modernization pathways are practical, scalable, and economically viable for firms across the casting and forging ecosystem.
Government	Framed the roadmap within a national-interest and readiness context, emphasizing DIB strength, system resilience, and long-term sustainment. This perspective reinforced modernization aligned with national security objectives, reduced structural barriers to adoption, increased manufacturing reliability across critical supply chains, and incorporated local and regional manufacturing realities.
Academia	Brought forward-looking, research-based insights focused on emerging technologies and advanced manufacturing practices. Academic stakeholders underscored the importance of next-generation workforce training models, stronger technology-transfer mechanisms, and data-driven manufacturing capabilities to support sustained innovation and long-term competitiveness within the C&F industry.

Figure 17. *Stakeholder Perspectives by Affiliation*

Stakeholder Communication

To support broad, balanced participation across the C&F ecosystem MxD implemented a structured stakeholder communication and outreach strategy designed to maximize awareness, encourage targeted engagement, and sustain participation across the workshop series. The team intentionally sequenced and refined outreach methodologies over time, combining broad ecosystem visibility with targeted recruitment and follow-up, to obtain comprehensive representation from industry, government, and academia. The approaches outlined below summarize how the team identified, contacted, and engaged stakeholders to support strong attendance and meaningful participation throughout the engagement process.

The targeted stakeholder list included a diverse cross section of federal defense organizations, national laboratories, and standards-setting bodies, which together provided strategic insight into DIB priorities, acquisition pathways, and manufacturing readiness requirements. In addition, the list encompassed industry primes, C&F producers, small and mid-sized manufacturers, equipment and technology providers, trade associations, research institutes, and academic partners.

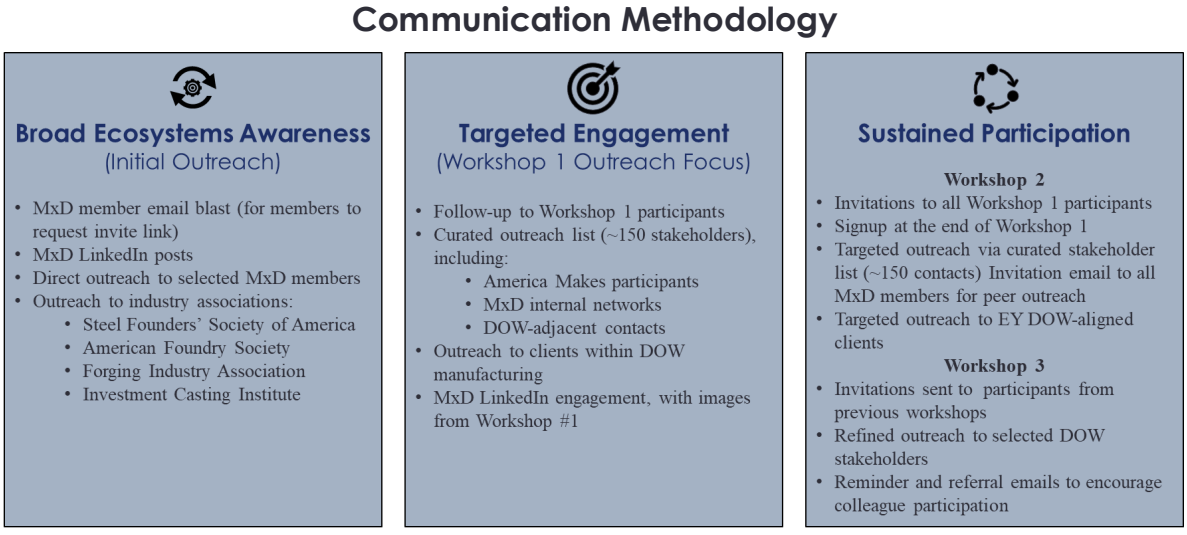


Figure 18. *Workshop Communications Strategy*

Limitations to Engagement

Workshop 1 received limited participation from the DOW and other government stakeholders, primarily due to the 2025 government shutdown and related logistical constraints. Despite these challenges, the sessions generated meaningful insights and fostered a unified industry perspective to propel change within the C&F industry.

For Workshop 2, several participants faced attendance challenges due to recovery efforts following the government shutdown. Some prospective attendees—particularly from government agencies—were unable to participate as they managed competing priorities after returning from the shutdown, indicating the need for continued engagement and follow-up. Additionally, adverse weather further complicated participation, as significant snowfall in the Chicago area the day prior to the event disrupted travel for attendees travelling from outside the region.

Stakeholder Interviews

The completion of Workshop 1 with casting, forging, die casting, and additive manufacturing professionals—along with industry SMEs—revealed an industry facing urgent structural challenges yet strongly aligned on a shared vision for modernization. The team intentionally selected participants based on the high-value insights they contributed during Workshop 1 group discussions and to enable deeper exploration of each segment of the manufacturing ecosystem. Across organizations of all sizes, interviewees described an industrial base constrained by legacy equipment, persistent workforce shortages, safety risks, supply chain vulnerabilities, and complex regulatory structures. At the same time, they emphasized the transformative potential of digital manufacturing technologies—automation, advanced process control, additive manufacturing (AM), simulation, and integrated data systems—to overcome longstanding inefficiencies and restore competitive capability.

SME Interviews Conducted
Defense Industrial Base
Additive Manufacturing
Workforce
Maritime Industrial Base
Investment Casting
Foundry Operations

Figure 19. *Knowledge Areas from SME Interviews*

Participants identified **safety**, **turnover**, **aging equipment**, and **manual processing** as primary pain points. While most companies possess deep technical expertise, high operator churn and a retiring workforce result in weakened process consistency and increased operational risk. Many facilities rely heavily on manual part handling, exposing workers to burn, repetitive strain, and hazardous temperatures.

The interviews also highlighted significant supply chain dependencies, including imported foams, metals, polymers, and specialty materials essential for C&F operations. Long lead times and the absence of domestic sources for key materials create bottlenecks and limit production capacity.

Despite these constraints, interviewees expressed optimism about the industry's desired future state, characterized by safer and more automated shop floors, greater use of simulation and digital twins, expanded additive manufacturing for tooling and legacy parts, and an integrated data environment that enables predictive insights and stable throughput. There was widespread agreement that improving process control**s** supported by modern sensors, Manufacturing Execution System (MES), and consistent KPI tracking—is one of the highest value modernization opportunities.

Participants also emphasized the need for workforce development, including pre-apprenticeship programs, hands-on training, and regional employer collaboration. Additionally, participants considered that an industry-wide approach, supported by associations like Forging Industry Associations (FIA), to be crucial for mobilizing shared solutions.

Finally, interviewees stressed that many modernization barriers are policy driven rather than technological. Procurement norms—especially within the DOW—limit the ability of small and midsize firms to compete, qualify for parts, or innovate legacy components. Addressing these systemic issues will be essential for unlocking the full potential of digital manufacturing within the C&F industry.

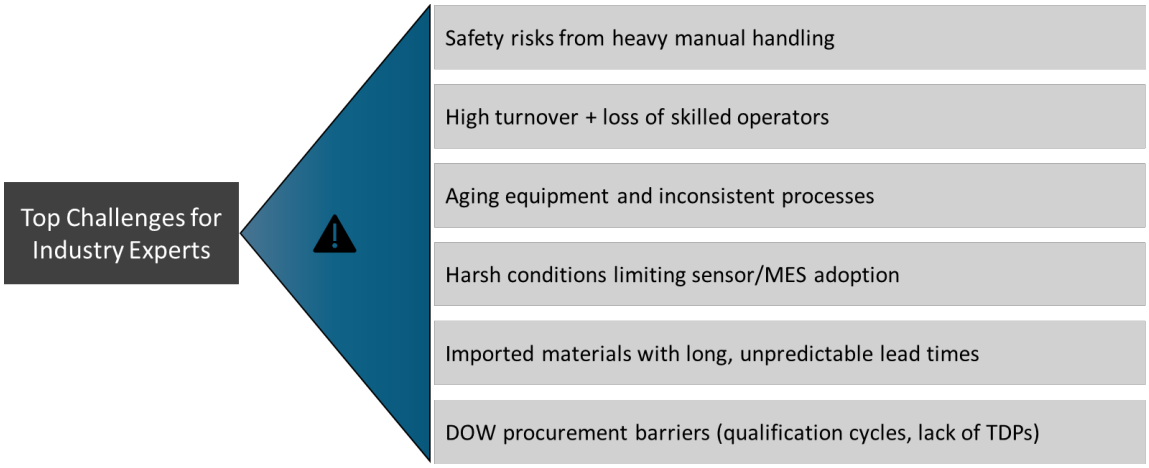


Figure 20. *Expert-Validated Challenges Across the C&F Industry*

Workshops

General Overview

The team designed each workshop to maximize engagement, deepen learning, and generate actionable results. Sessions built sequentially, using insights from prior discussions to maintain strategic alignment and support progressive development. Each workshop followed a clear digital plan with defined objectives, activities, and deliverables, producing outputs that directly informed analysis and recommendations.

Figure 21. *Facilitators conducting a small group breakout*

Three goals guided the effort:

1. Develop a clear understanding of the current state of the C&F industry.
2. Identify and prioritize critical issues across capacity, technology, workforce, and supply chain.
3. Examine root causes affecting overall industry performance

Participants engaged with stakeholders, collaborated with peers, and took part in structured discussions that enabled deeper insight and collective problem-solving.

Workshop 1 – "Casting and Forging Industry Challenges"

Overview

Objective: Identify and prioritize industry challenges.

The initial workshop aimed to identify the most critical pain points facing the C&F industry by first establishing a shared understanding of its current state. Participants collaborated to analyze challenges across technology, supply chain, workforce, and capacity (shown in Appendix B), while also highlighting strategic opportunities for innovation within the DIB.

Objectives	
	Develop an understanding of the current state of the C&F industry environment, including key challenges within the US
	Identify and prioritize the most critical challenges across the C&F industry within the areas of capacity, technology, workforce, and supply chain
	Explore root causes impacting the C&F industry

Figure 22. *Workshop 1 Objectives*

Approach

The team structured the workshop to align participants, create a common understanding, and drive prioritization by integrating quantitative market data with qualitative industry insights. It combined plenary discussions with facilitated breakout sessions grounded in common market trends and research. The team intentionally designed breakout sessions to:

- Surface and prioritize critical industry pain points, allowing participants to validate and refine challenges related to operations, technology, workforce, and supply chain dynamics.
- Examine root causes of prioritized challenges, enabling participants to move beyond surface level symptoms and identify systemic drivers and interdependencies. Groups completed fishbone diagram exercise to determine actual root causes.

Each breakout group included six to eight participants. A pre-workshop survey captured perceived alignment to one of four challenge themes and informed group assignments. Grouping participants with similar perspectives enabled deeper, more detailed discussions; however, it also limited cross-pollination of ideas across themes and reduced exposure to alternative viewpoints that might have surfaced adjacent or interdisciplinary insights.

The facilitators leveraged participant input throughout these discussions to validate, refine, and prioritize challenges through guided dialogue and structured analysis. Overall, this approach validated the current state of the C&F environment, clearly articulated the most pressing industry pain points, and provided a disciplined foundation for opportunity exploration in subsequent workshops.

Furthermore, the workshop focused on five key analytical areas that structured discussion and facilitated participant alignment during both plenary and breakout sessions.

1. **Industry Context and Market State –** Establishing a common understanding of the current C&F landscape, including macro trends, operational constraints, and external pressures affecting the DIB. Through the plenary session, stakeholders received an overview of key market trends and analysis through MxD and its partner's research.
2. **Identification of Critical Pain Points –** Documenting the most significant challenges related to capacity, technology adoption, workforce sustainability, and supply chain resilience.

3. **Prioritization of Challenges –** Evaluating pain points based on perceived impact and urgency to focus attention on the most critical issues.
4. **Root Cause Analysis –** Distinguishing between symptoms and underlying systemic issues driving industry challenges.
5. **Opportunity Framing (Pre-Ideation) –** Highlighting areas where future innovation or intervention may be warranted, without advancing into solution development or vendor specific discussions.

Figure 23. *Workshop 1 Keynote*

Key Insights and Highlights

The following key insights and highlights reflect outputs from Workshop 1 discussions and participant engagement. These themes served as guiding principles and represent the collective experience and priorities identified by industry participants, informing strategic decisions and the structure of the roadmap.

- **Complex and burdensome DOW procurement and contracting processes.** Stakeholders highlighted lengthy timelines, rigid specifications, and high compliance requirements that increase cost, risk, and barriers to participation—particularly for small and mid-sized suppliers.
- **Volatile and unreliable demand signals.** Inconsistent forecasting and short-term contracting cycles create uncertainty, discouraging capital investment and resulting in underutilized capacity across the industrial base.
- **High cost structure and constrained access to capital.** Rising energy costs, significant CapEx/Opex requirements, and prolonged equipment downtime strain operations, while certification requirements and cashflow limitations disproportionately impact smaller suppliers.
- **Fragmented and underdeveloped data infrastructure.** Lack of standardized data models, inconsistent governance, and limited data-sharing protocols hinder integration, analytics adoption, and overall operational efficiency.
- **Workforce shortages and talent pipeline challenges.** An aging workforce, limited training pathways, and insufficient digital skill development reduce industry capacity and limit readiness for modernization.
- **Limited collaboration and data sharing across the ecosystem.** Siloed operations, lack of shared standards, and reluctance to exchange information lead to redundant efforts and increase barriers to entry for broader participation.

Workshop 2 – "Casting and Forging Actionable Solutions"

Overview

Objective: Translate validated challenges into actionable solutions

Workshop 2, *Understanding Potential Solutions to Advance Casting & Forging through Digital Manufacturing*, convened on December 9, 2025. Building on the challenges identified during Workshop 1, this session focused on developing actionable, digitally enabled solutions to strengthen the C&F industry in support of the DIB.

The workshop engaged 31 participants from the DOW, academia, and manufacturers of varying sizes. Through highly structured and collaborative working sessions, participants generated feasible, time-phased recommendations aligned with industry needs, DOW priorities, and modernization goals.

Approach

The workshop followed a structured sequence designed to move participants from shared understanding to clear, actionable solutions.

Objectives	
	Identify and analyze root causes
	Develop practical, digitally–enabled solutions
	Prioritize proposed solutions into actionable recommendations within focus areas: Technology, Workforce, Supply Chain, and Capacity

Figure 24. *Workshop 2 Objectives*

Framing the Challenges: Workshop 2 commenced with an overview of the challenges identified in Workshop 1, where participants reviewed 13 critical problem statements across four focus areas: Technology, Workforce, Supply Chain, and Capacity. This established a shared understanding of issues and challenges such as complex procurement processes, talent shortages, data gaps, legacy equipment, and fragmented industry standards.

Session 1 Root Cause Analysis: In the initial breakout session, cross-functional teams performed root cause analyses on assigned problem statements using a structured template. Teams documented three to five actionable root causes for each challenge. Groups shared insights to stimulate broader thinking and collaborative idea generation.

Breakout Session 2 Solution Development: In the second breakout, teams focused on solution development, translated root causes into practical solutions, and prioritized them using an impact–effort framework. The were then categorized into short-term (zero to one year), mid-term (one to three years), and long-term (three or more years) categories according to their projected timelines.

Readouts and Synthesis: Each proposal outlined key stakeholders, anticipated risks, and barriers to adoption. Workshop 2 concluded with concise group readouts and synthesis of cross-cutting themes, which collectively informed the digital fabric roadmap for the C&F industry.

Key Insights & Highlights

- **Replace outdated data assets with modernized digital sources.** Reliance on legacy 2D CAD drawings continues to constrain efficiency and accuracy. Establishing a defined conversion pathway and creating an ongoing refresh process for digital assets is necessary for teams to operate from authoritative, modern data sources that reduce rework and accelerate production workflows.
- **Reinforce human oversight and talent development.** Human expertise remains essential for quality assurance, accountability, and strong program governance. As the industry evolves, building digital literacy, systems knowledge, and modern manufacturing skills enables effective oversight, reduces risk, and drives continuous improvement.
- **Evaluate organizational readiness to tailor modernization pathways.** Recognizing differences in maturity and capability across organizations enables more targeted planning, focuses efforts on value-generating data and capabilities, and supports realistic, phased advancement.

- **Promote collaboration over competition to lower participation barriers.** Shared standards, transparent practices, and cooperative problem-solving reduce organizational hesitancy, simplify participation, and build trust across the industrial base—especially among smaller manufacturers.
- **Increase supply chain transparency to strengthen planning and resilience.** Improved visibility into timelines, dependencies, and material flows is essential to address long-standing bottlenecks, enhance scheduling accuracy, and support industry-wide progress.
- **Support small suppliers and streamline government engagement.** Simplifying certification, compliance, and cash-flow requirements, paired with sponsored support and clear guidance, will broaden supplier participation, build industry capacity, and improve DOW collaboration.

Workshop 3 – "Validating Inputs for Digital Manufacturing Roadmap"

Overview

Objective: Validate, refine, and prioritize solutions into roadmap-ready projects

Workshop 3 convened on January 21, 2026, and assembled 22 representatives from the listed stakeholder groups and previous workshop participants. Session priorities advanced from challenge identification to solution prioritization. Participants evaluated proposed solutions over 28 final solutions based on industry needs, feasibility, alignment with DOW priorities, and the urgency of modernization. This collaborative approach fostered a robust exchange of ideas and enabled participants to collectively identify the most promising and impactful solutions based on real-world constraints and opportunities.

Objectives	
	Refine priority C&F solutions based on insights and outputs from prior workshops
	Facilitate stakeholder dialogue for solution alignment, required timelines and project development
	Prioritize projects to guide official roadmap development

Figure 25. *Workshop 3 Objectives*

Approach

The team designed Workshop 3 to maximize participation and ensure transparent evaluation of proposed projects. After opening remarks from MxD leaders, the team divided participants into small groups and rotated them through several rooms. Each room displayed a curated set of the thirty final projects. This gallery-walk format allowed stakeholders to review each proposal directly and provide comments, suggestions, and critical feedback on implementation timelines, recommended approaches, key activities, and investment needs.

The interactive format promoted focused engagement, encouraging participants to share insights and perspectives across a wide range of project concepts. The process facilitated comprehensive input on the practicality and impact of each proposal and promoted collaborative problem-solving by drawing on the collective expertise present.

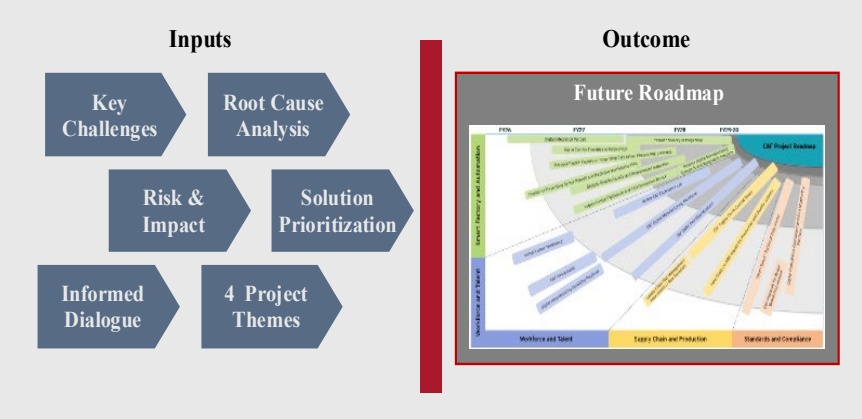


Figure 26. *Strategic Contributions to the Roadmap*

The second half of the workshop shifted toward deeper engagement and thematic prioritization. The team reorganized participants into focused working groups, each responsible for a distinct set of proposed solutions. Each group held structured discussions on key activities, implementation approaches, and the anticipated time and investment required for each solution. The goal was not to reach consensus but to spark thoughtful, multidimensional conversations and encourage participants to consider practical realities from various perspectives. These debates surfaced critical considerations, challenged assumptions, and highlighted potential barriers and enablers that ultimately informed the final roadmap.

Through inclusive, dialogue-based engagement, Workshop 3 laid the groundwork for consensus and actionable strategies, ultimately providing a strong foundation for the digital manufacturing roadmap with final solutions addressing both immediate and future industry needs.

4 Project Themes*	
	Smart Factory & Automation
	Workforce & Talent
	Supply Chain & Production
	Standards & Compliance

Figure 27. *Final Project Themes*

***Please note:** As stakeholder engagement broadened and matured during the workshops, the project themes were refined and expanded to provide a comprehensive basis for advancing the C&F industry.

Key Insights & Highlights

The following key insights and highlights are outputs from Workshop 3 discussions and participant engagement. Serving as guiding principles, these points reflect the collective experience and priorities identified by industry participants, informing strategic decisions and the roadmap structure.

- **An inventory assessment is necessary.** Catalogue previous C&F workshops and related studies to establish a thorough inventory of technologies and insights, identify existing gaps, and guide future strategic planning. This is a crucial first step to facilitate a clear understanding of current resources available.
- **Validation of the need for standardized data governance and digital adoption frameworks.** Stakeholders reinforced the importance of defining common standards for data ownership, sharing, and usage, supported by a unified digital adoption playbook.

- **Address outdated data sources.** Outdated assets like 2D CAD drawings referencing obsolete standards reduce efficiency; determine a path forward to updating assets and establish a streamlined process to confirm use of updated, modernized data sources.
- **Incorporate human oversight.** Incorporate human review into critical processes to promote quality assurance and accountability. Human involvement is fundamental to effective project management and progress. Additionally, advancing the C&F industry requires a highly skilled workforce and strategic talent development. Emphasizing workforce development strengthens oversight and fosters a culture of continuous improvement, paving the way for the industry to remain competitive and prepared for future challenges.
- **Encourage strategic stakeholder engagement.** Identify key DOW stakeholders to verify the right people are involved and in place to drive progress and expedite approvals. Past challenges in sharing materials stemmed from unclear policies and standards.
- **Conduct needs prioritization exercises.** Perform comprehensive needs assessments to establish a prioritized list of critical requirements. Clearly defining these essential criteria will support effective resource allocation and informed decision-making.
- **Organizational maturity and readiness evaluations are vital.** Acknowledge that organizations differ in their readiness and capacity. Conducting a comprehensive assessment will help determine essential data requirements and highlight value-generating opportunities unique to each organization.
- **Encourage collaboration over competition.** Promote collaboration over competition to ease participation barriers. A cooperative approach will alleviate concerns about infringing competitive advantages.
- **Address supply chain transparency.** Supply chain visibility continues to be a significant concern within the manufacturing industry. Enhanced knowledge sharing and the provision of precise timelines are essential for advancing progress in C&F.
- **Support smaller suppliers and streamline government engagement.** Collaborate to address process bottlenecks that hinder supplier engagement with the government, such as complex certification requirements and cash flow constraints. Facilitate greater participation and enhance industry efficiency by offering educational resources and sponsored initiatives.

Insights Analysis

Overview

This section synthesizes insights from all data sources and explains the analytical process used to translate raw inputs into a structured roadmap. The team drew upon three stakeholder workshops, one-on-one interviews, and a comprehensive research review to build an integrated evidence base. The research review established quantitative context, which the team aligned with qualitative insights from the workshops and interviews to create a cohesive analytical foundation.

The analysis applied a lens across the four project dimensions—capacity, technology, workforce, and supply chain—to reveal systemic patterns rather than isolated issues. In Workshop 1, stakeholders surfaced core challenges, pain points, and root causes; the research review validated these with data, enabling the team to distill them into 13 high-impact problem statements. Workshop 2 refined these statements and generated targeted solution concepts designed to address the most critical barriers. The team then translated solution concepts into structured projects, each linked to one or two problem statements and composed of four to six solution components.

Workshop 3 validated and prioritized the resulting projects, stress-testing feasibility, sequencing, and alignment with modernization objectives. Between workshops, the team conducted detailed analytical work to normalize inputs, test assumptions, and ensure traceability from evidence to recommendation.

By integrating inputs across workshops, interviews, and research, the team created a modernization pathway. This evidence-driven approach ensures each roadmap element links directly to stakeholder insights, empirical data, and cross-workshop validation. The final roadmap reflects the industry's cross-cutting themes and provides a structured framework for sequencing, investment, and strategic decision-making across the casting and forging ecosystem.

Problem Statements – Inputs and Insights Integration

Inputs

Stakeholders developed problem statements through a structured, data-driven process that synthesized research, workshop outputs, and root cause analysis. Efforts began with the review of research topics and supporting evidence to establish baseline conditions across the C&F ecosystem. During Workshop 1, stakeholders participated in two sequential breakout activities:

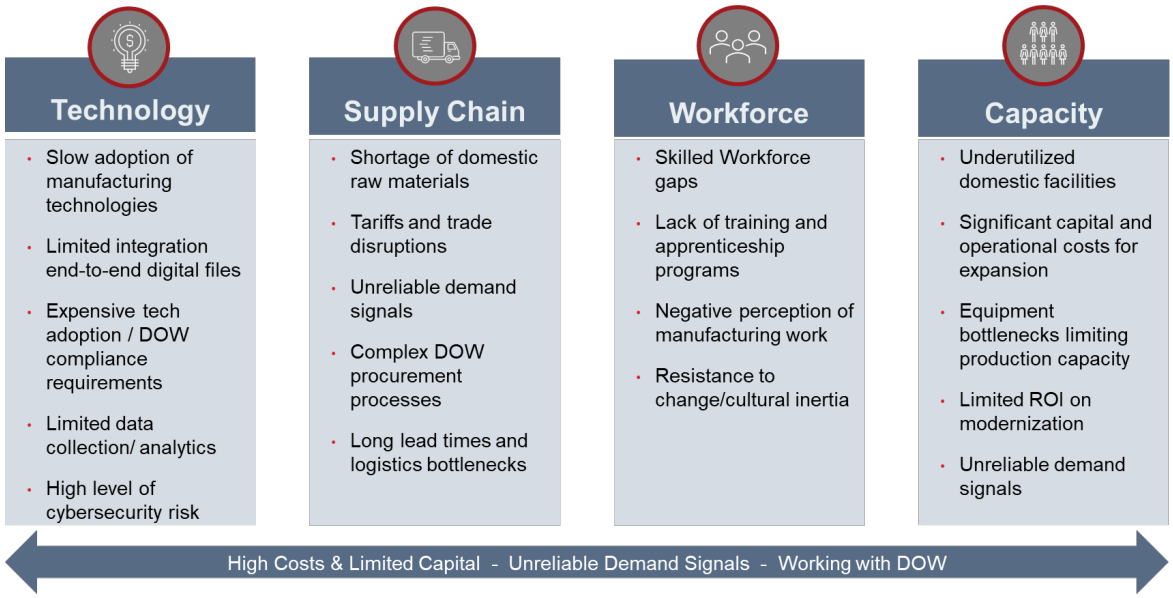


Figure 28. *Consolidation of Industry Challenges Across the Four C&F*

- **Challenge Identification (WS1-Breakout1)** Identified the most pressing issues across the Supply Chain, Capacity, Technology, and Workforce domains. Stakeholders highlighted challenges such as 50% cost increase, shortages of domestic raw materials, months-long lead times for forging and molding equipment, and frequent downtime where critical machinery repairs can take up to six months. Technology challenges were similarly acute, including the widespread continued use of 2D drawings in place of digital models, limited end-to-end integration of technical data, and expensive DOW compliance and inspection requirements, which can account for up to 50% of total part cost. Workforce-related pain points include severe skilled labor shortages, the erosion of vocational pipelines, and negative perceptions of manufacturing among younger generations. The key themes distilled from these challenges are shown in Figure 28, which captures the cross-domain patterns emerging from this first analysis.

- **Root-Cause Analysis (WS1 - Breakout2):** Stakeholders used fishbone diagrams to examine the deeper drivers behind these challenges. The team then consolidated insights across all workshop groups, identifying recurring patterns such as process and quality inconsistencies, skills gaps, technology and data shortfalls, cultural resistance, and policy-driven burdens. The team cross-mapped themes against all four domains to identify. Appendix C5 presents the most important themes identified during our analysis. To achieve this, the team collected all words used in the root cause analysis, standardized them, and then categorized each word according to one of seven predefined categories. This method enabled systematic grouping of the language so that each theme accurately reflected the underlying issues discussed by stakeholders.

- **Cross-Cutting Challenges (Analysis**): Using a systematic approach, the team analyzed Workshop 1 outputs and standardized 16 core challenges across Supply Chain, Capacity, Technology, and Workforce. Cross-domain comparison revealed enterprise-level obstacles that repeatedly constrain the C&F ecosystem government-driven barriers, skilled-workforce shortages, unreliable DOW demand signals, high operating costs with limited capital, and gaps in digital data and end-to-end technical files. Appendix C6 presents the full cross-cutting analysis and shows how these issues emerged from the standardized set.

    - **To identify the cross-cutting challenges, MxD and its partners applied a rigorous, multi-step analytical approach:**

        - **Standardization of Inputs:** Compiled and normalized all challenges from Workshop 1 into a structured list of 16 recurring themes across the four domains.

        - **Root-Cause Synthesis:** Analyzed outputs from the fishbone exercises to understand deeper drivers—such as process standardization gaps, skills shortages, cultural inertia, data limitations, and policy-driven constraints—that cut across organizational and operational boundaries.

        - **Cross-Domain Mapping:** Assessed each challenge and root-cause category for its prevalence across multiple domains. Flagged challenges that appeared repeatedly—impacting technology adoption, workforce stability, supply chain reliability, and production capacity—as cross-cutting.

Conversion to Problem Statements

Building on the standardized challenge set and the cross-cutting analysis, the next step in the methodology involved converting these insights into a clear, actionable set of **problem statements.** In the context of this roadmap, a *problem statement* serves as a concise, evidence-based articulation of a systemic barrier that inhibits modernization, resilience, or readiness across the casting and forging ecosystem. Each statement synthesizes multiple sources of evidence—research, stakeholder insights, and empirical pain points—into a structured definition of the obstacle that must be addressed to advance capability.

To develop the problem statements, the team translated the 16 standardized challenges and the identified cross-cutting themes into distinct, high-impact issues that reflected the underlying root causes rather than surface-level symptoms.

This required consolidating overlapping themes, differentiating root-cause drivers from manifestations, and confirming that each problem statement represented a barrier that both (a) directly affects defense-critical production and (b) can be meaningfully addressed through targeted modernization interventions.

A **quantitative weighting methodology** was applied to prioritize which challenges would be elevated into problem statements. The team scored each standardized challenge using a two-factor model:

- **Recurrence,** which measured how frequently a challenge appeared across workshop groups and domains; and
- **Severity**, which assessed the degree of operational, financial, or strategic impact associated with the challenge.

Challenge	Recurrence Score	Severity Score	Total Weight (Max = 6)	Reasoning
1. Government DoD Barriers	3 (mentioned in all 4 categories)	3 (costly, risky, complex)	(6/6)	• Cited repeatedly as a major obstacle to profitability, modernization, and participation • Includes CMMC, AS9100, legacy specs, and procurement complexity

Figure 29. *Sample Challenge Weighting Used to Derive Problem Statements*

To illustrate how the standardized challenges were transformed into formal problem statements, the table below shows an example using one of the highest-weighted cross-cutting challenges. This example demonstrates how combining recurrence, severity, and supporting evidence formed a defensible, analytically derived problem statement.

Scores ranged from one to three per dimension, resulting in a maximum possible weight of six. Challenges related to DOW and government barriers, skilled workforce shortages, unreliable demand signals, limited capital for modernization, and technology and digital data shortfalls consistently ranked at the high end of the scale due to their prevalence and magnitude of impact. These high-weight challenges formed the foundation of the final set of 13 problem statements, with each statement reflecting an issue that was both widely experienced and highly consequential within the C&F industry. By concentrating on these top-tier challenges, the analysis established a structured and defensible basis for modernization roadmap development and reinforced alignment between subsequent initiatives and the industry's most critical barriers.

Problem Statement 1:
Working with DOW: Complex DOW procurement processes/timelines, stringent product specifications, and end-item acquisition methods significantly hinder industry participation.

Figure 30. *Example Problem Statement*

Problem Statement Impact on Roadmap

The 13 problem statements served as the bridge between stakeholder-identified challenges and the final modernization roadmap, directly shaping its focus, structure, and sequencing. Each problem statement captured a validated, high-impact barrier, supported by recurrence across Workshop 1 groups, reinforced through root cause analysis, and prioritized using quantitative weighting. Together, they provided a defensible basis for identifying where modernization efforts would have the greatest effect.

Highly weighted issues, including government and DOW barriers, skilled workforce shortages, unreliable demand signals, limited capital for modernization, and gaps in digital data, became the focal points for solution development in Workshop 2 and subsequent project formulation. Each roadmap project was mapped back to one or more problem statements, establishing clear traceability between recommended actions and documented, widely experienced pain points within the C&F ecosystem.

This alignment supported the roadmap to emphasize initiatives that address systemic constraints while

maximizing operational relevance, modernization momentum, and industrial base resilience. As a result, the final roadmap reflects an integrated evidence base in which sequencing, timelines, and investment pathways are informed by the severity, prevalence, and strategic importance of the underlying problem statements.

Solution Statements – Inputs and Insights Integration

The solution statements developed during Workshops 2 and 3 served as the foundation for shaping the future projects included in the C&F Digital Fabric Roadmap. Following the identification and ranking of the industry's most critical challenges in Workshop 1, Workshop 2 translated these challenges into structured solution statements using root cause analysis, the "5 Whys," and evaluation criteria such as feasibility, time horizon, and stakeholder ownership. Each solution statement, addressing areas such as digital interoperability, supply chain visibility, workforce upskilling, or demand signal forecasting, was intentionally narrow in scope, digitally focused, and aligned with short- to mid-term implementation horizons. These statements provided a consistent input for identifying where targeted technology interventions could most effectively reduce friction.

Workshop 3 focused on validating, refining, and prioritizing these solution statements and organizing them into actionable projects with defined objectives, success measures, and implementation pathways. Participants assessed proposed solutions based on impact, effort, adoption readiness, and DOW ownership potential. This process resulted in a set of future projects aligned to previously identified themes, including digital file standardization, traceability tools, condition-based maintenance sensor kits, workforce readiness initiatives, cybersecurity preparedness, and improved demand signal sharing mechanisms. Through this iterative approach, the workshops translated broad industry challenges into a coordinated portfolio of projects supported by stakeholder input, validated root cause analysis, and structured feasibility considerations.

These future projects reflect the cumulative insights from the entire workshop series: **problems identified in Workshop 1 → root causes analyzed and solution statements drafted in Workshop 2 → prioritized, roadmap-ready projects validated in Workshop 3.** The solution statements acted as the bridge between challenge identification and project definition, ensuring that every recommended future project is both grounded in industry need and designed for digital modernization of the C&F ecosystem.

Project Validation – Inputs and Insights Integration

Project validation marks the transition from early analysis to decision-ready initiatives, as reflected in the roadmap development process. At this stage, stakeholders actively tested and refined proposed projects before advancing them for prioritization.

Workshop 3 served as the primary validation forum. During this session, participants evaluated each proposed project's feasibility, potential impact, sequencing, and strategic relevance. Stakeholders challenged underlying assumptions, identified key dependencies and barriers, and assessed readiness to proceed. Guided by the structured progression shown in the visual, participants distinguished between initiatives prepared to advance and those requiring foundational conditions (e.g., data maturity, workforce readiness, governance clarity, or broader ecosystem coordination) before moving forward.

Insights from this validation effort informed the subsequent refinement phase. The team adjusted project scope, clarified dependencies, and aligned timelines to reflect realistic implementation pathways. These updates strengthened the roadmap structure and established priorities in a logical, stakeholder-endorsed sequence.

The results presented in this section capture the outcome of that process: a validated and prioritized set of 30 modernization projects grounded in stakeholder evidence to develop the roadmap.

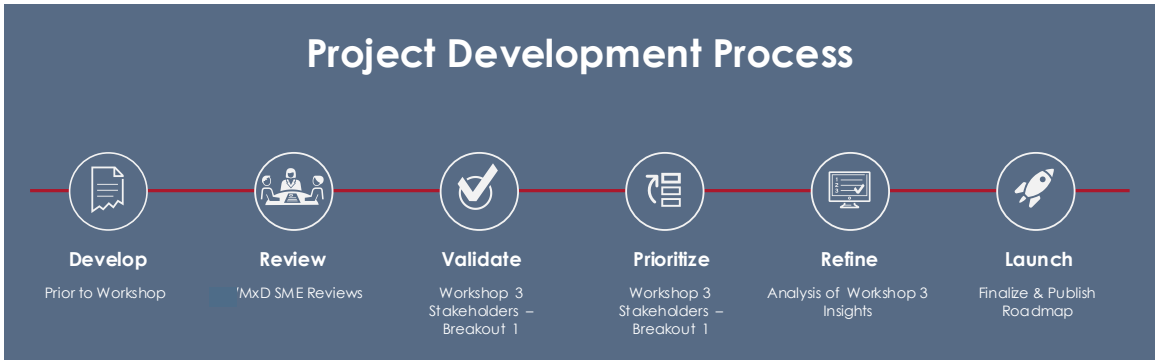


Figure 31. *Project Development Process*

Inputs

The team developed initial draft projects prior to the workshop and refined them based on feedback from MxD and its partners' subject matter resources before finalizing and delivering detailed project statements. For each project, the team produced a project poster that provided a comprehensive overview of the initiative, as shown in Appendix E2. Each project addressed one to two problem statements and incorporated two to six associated solution statements.

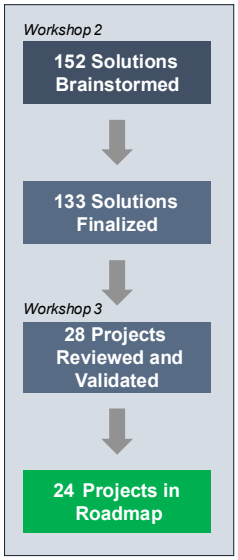


Figure 32. *Project Development Process*

- **Project Development (Preworkshop 3):** Before Workshop 3, the project team consolidated all solution statements generated in Workshop 2 and organized them into preliminary modernization projects. Each draft project grouped four to six related solution concepts and mapped them back to validated problem statements to establish clear lineage and strategic relevance. MxD and its partners then conducted an internal review to assess project completeness, feasibility, and structural coherence. This pre-workshop development phase confirmed that each draft project had a clear objective, defined outcomes, and an explicit link to root cause drivers and modernization priorities, providing stakeholders with a well-formed baseline set of initiatives to review, validate, and refine during Workshop 3.

- **Project Review – Validation (WS3 – Breakout 1):** In During Workshop 3, stakeholders conducted a structured review of all proposed modernization projects to assess viability, relevance, and alignment with ecosystem needs. Using a gallery walk format, participants evaluated project posters outlining each initiative's scope, expected outcomes, required enablers, and links to validated problem statements. Feedback surfaced key feasibility considerations, including digital infrastructure gaps, challenges scaling automation, dependencies on DOW policy changes, workforce skill limitations, and risks associated with unclear ownership and resource constraints. Stakeholders offered targeted input to strengthen project definitions, build shared understanding of project purpose, and highlight areas requiring clarification, refinement, or consolidation. Insights from this session reflected practical execution conditions and informed the final roadmap prioritization. Appendix E4 shows representative participant feedback captured through engagement techniques such as sticky notes and butcher paper, which also supported active participation.

Stakeholder Feedback Themes	
	Digital Foundations & Standards: Clean data and common standards enable everything else
	Cyber & Compliance by Design: Secure and compliant from day one
	Pilot-to-Scale & ROI: Prove value early, then expand
	Sensor & Quality: Measure processes to improve outcomes
	Workforce & SMB Enablement: Tools and skills that fit real manufacturers
	Governance & Accountability: Clear ownership and decision rights
	Supply-Chain Visibility: Understand and manage industrial dependencies
	Efficiency & Resource Performance: Efficiency gains realized through improved quality and throughput

Figure 33. *Feedback Themes from Workshop 3*

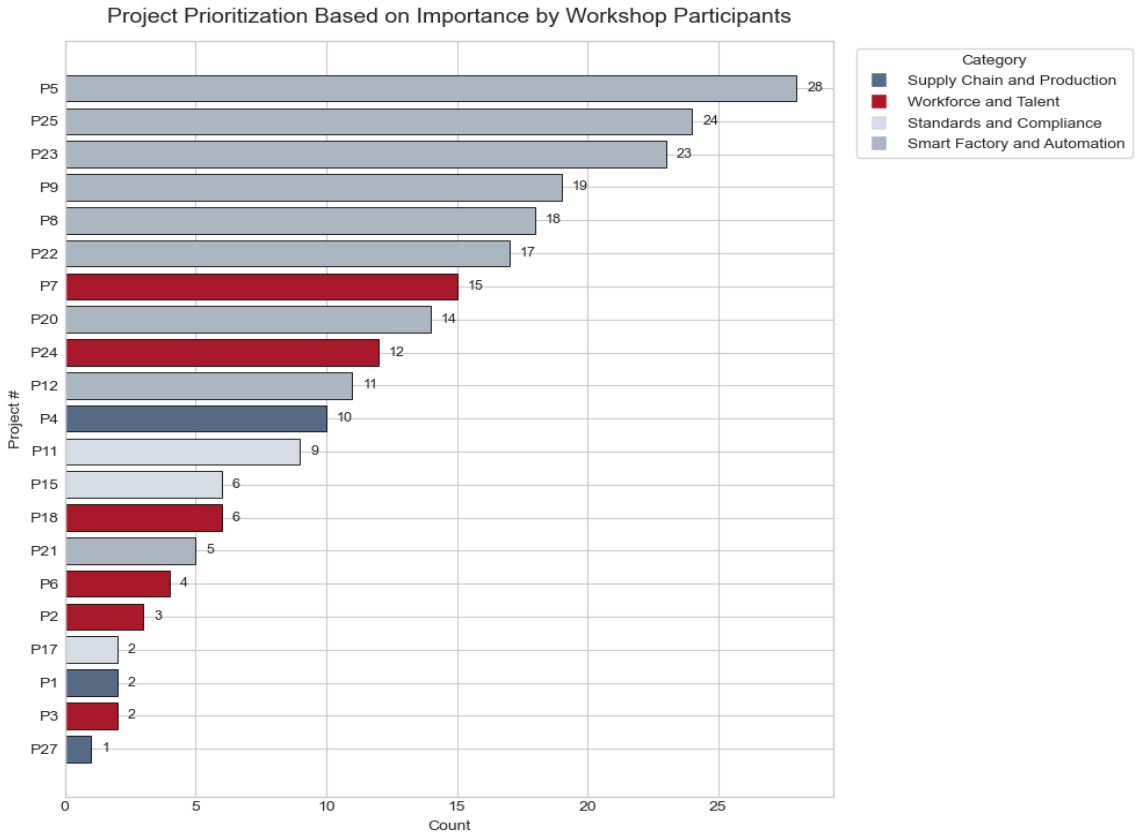


Figure 34. *Workshop 3 Breakout 1 Project Priority Ranking*

- **Project Review- Prioritization (WS3 - Breakout 1):** Stakeholders participated in a structured prioritization exercise in which they reviewed eight project posters and used a sticker-based method to rank their top three initiatives based on ease of implementation and potential impact. This activity produced a clear, visual view of stakeholder preferences and distinguished projects with near-term, measurable relevance to the DIB from those requiring further validation or refinement. The graph below summarizes the voting results, highlighting the projects participants viewed as highest priority
- **Project Development (WS3 - Breakout 2):** The team structured Breakout 2 to translate stakeholder feedback into more actionable project definitions by guiding participants through focused discussions on a curated set of four to six modernization projects. To anchor these discussions, stakeholders revisited each draft project charter alongside insights synthesized in Breakout 1 and assessed the projects using a structured lens aligned with the format shown in Appendix E3. Using this reference, participants examined key activities, analyzed required data inputs, identified policy or infrastructure bottlenecks, and clarified feasibility constraints that could affect implementation. Figure 35 illustrates the standardized visual completed during the session, capturing how groups worked through project phases, risks, dependencies, and value pathways to support more consistent and comparable analysis across teams. To broaden perspectives and reduce groupthink, the session design emphasized practical, experience-based insights that may not have surfaced during earlier validation steps. Each group contributed inputs that informed project refinement, including:
    - **Key Activities** – specific actions required to advance each project (e.g., data collection, policy analysis, system integration).
    - **Recommended Phases** – a sequenced view of how work should progress, such as initial data retrieval, analysis, and piloting.
    - **Implementation Timeline** – when various phases could reasonably occur and what dependencies shape the pacing.

- **Dependencies and Risks** – external conditions, system constraints, stakeholder participation, or data-sharing considerations required for success

<table>
<tr><th colspan="5">P26: Procurement Policy Optimization via AI Analysis of ERP Data</th></tr>
<tr><th colspan="5">Key Activities</th></tr>
<tr><td colspan="5">• Looking at historical data and how to prevent mistakes
• Start with big programs (F-35 production, land vehicles) – programs that are active procurement
• Run on future vertical lift to collect data
• C&F ERP data doesn't help
• Need visibility into supply chain
• AI tools that can connect across programs and spot anomolys
• Identify what in the currentl policy is creating bottlenecks
• Industry wide – bigger than C&F
• Look at data to identify bottlenecks, look at policies associated with it to find bottlenecks (e.g., availability of rare earth mineral)
• How much engineering work can they do concurrently</td></tr>
<tr><th colspan="5">Identify Recommended Phases</th></tr>
<tr><td colspan="2" rowspan="2">• Quality of data needs to be good enough to even make an analysis out of it
• Getting this data will cost small manufacturers plenty of money
• In the big programs, are there a systematic issue?
• Concurent engineering
• Prevent bottlenecks
• Key Supply Chain Issue – nobody gets 100% of the work
• Identify what policy elements are, but addressing them is too difficult</td><th colspan="3">Timeline</th></tr>
<tr><td>Rertrieve quality data</td><td>Analyze the data</td><td>Pilot on 3 different programs</td></tr>
<tr><th colspan="3">Value Delivered</th><th colspan="2">Performance Indicators</th></tr>
<tr><td colspan="3">1. Provided data-backed insights into procurement bottlenecks.
2. Supported targeted policy changes that reduce lead times and improve throughput.
3. Built transparency and trust between industry and government.
4.
5.
6.</td><td colspan="2">• # of ERP systems analyzed
• Average lead time (order to shipment)
• % of delayed orders
•
•
•</td></tr>
<tr><th>Dependencies</th><td>•
•
•</td><th>Risks</th><td colspan="2">• How much foundy/forge want to share IP or data</td></tr>
</table>

Figure 35. *Example Project Poster*

Insight Integration

As validation activities in Workshop 3 concluded, the project team shifted from assessing project viability to integrating insights from all breakout sessions into the refinement of each modernization initiative. Feedback from the gallery walk, prioritization exercise, and in-depth discussions provided a comprehensive view of stakeholder expectations, feasibility considerations, and operational constraints. These insights, covering dependencies, digital infrastructure gaps, implementation phasing, and measures of value, served as key inputs to sharpen each draft project. By consolidating and applying this evidence, the team confirmed that projects advancing into the roadmap reflected both strategic relevance and practical execution conditions. This integration bridged validation and refinement, allowing the roadmap to mature from a set of discrete ideas into a cohesive, stakeholder-informed portfolio of implementation-ready modernization initiatives.

Appendix

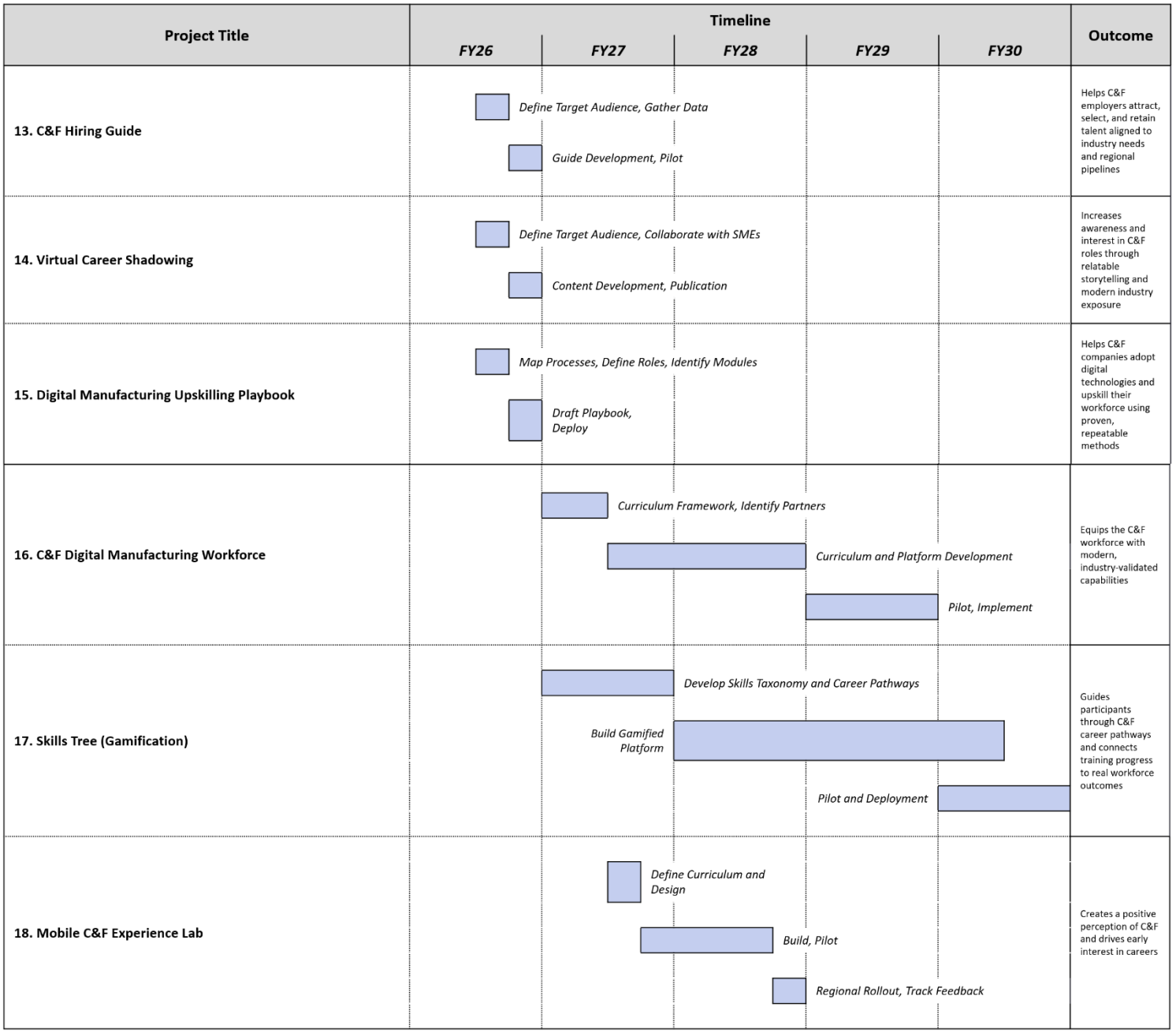
Appendix A – Projects Timeline

Project Title	Timeline					Outcome
	FY26	*FY27*	*FY28*	*FY29*	*FY30*	
1. Digital Integration Testbed	*Define and Design Architecture, Identify SMEs*	*Build, Test, Identify Manufacturers to Pilot*	*Pilot On-Site Pop-Up Testbeds*			De-risks integration and accelerates adoption of digital tools across the C&F industry
2. Foundry Sensor Retrofit and Predictive Maintenance Pilot		*Foundry Current State Assessment and Kit Deployment*	*Pilot in Foundries, Depict KPIs via Dashboard*			Reduces foundry unplanned downtime and maintenance cost while extending the life of legacy equipment
3. Forge Shop Sensor Retrofit and Predictive Maintenance Pilot		*Forge Shop Current State Assessment and Kit Deployment*	*Pilot in Forge Shops, Depict KPIs via Dashboard*			Reduces forge shop unplanned downtime and maintenance cost while extending the life of legacy equipment
4. Digital Twin for Foundries		*Identify Foundry Data, Deploy Sensors in Foundries, Engage with SMEs*	*Data Analytics, Continuous Monitoring, Process Improvement*			Reduces foundry scrap and downtime while guiding operators to optimal set-ups in real time
5. Digital Twin for Forge Shops		*Identify Forge Shop Data, Deploy Sensors in Forge Shops, Engage with SMEs*	*Data Analytics, Continuous Monitoring, Process Improvement*			Reduces forge shop scrap and downtime while guiding operators to optimal set-ups in real time
6. Playbook/Toolkit: Foundry Data-Driven Process Improvements		*Data Collection, Prioritize Foundry Processes*	*Playbook/Toolkit Development and Test*	*Pilot in Foundries, Engage SMEs*		Allows small/medium foundries to achieve quick analytical wins with minimal capital

Project Title	Timeline					Outcome
	FY26	FY27	FY28	FY29	FY30	
7. Playbook/Toolkit: Forge Shop Data-Driven Process Improvements			*Data Collection, Prioritize Foundry Processes*	*Playbook/Toolkit Development and Test*	*Pilot in Foundries, Engage SMEs*	Allows small/medium forge shops to achieve quick analytical wins with minimal capital
8. Legacy Design Digitization and CAD Conversion Service			*Collect Inventory of 2D/3D Drawings*	*Pipeline Build, Pilot One Example*	*Scale and Sustain*	Converts legacy drawings into validated 3D models, cutting NRE and unlocking model-based workflows
9. Digitally-Enabled Quality and Measurement Inspection			*Gathering Baseline Quality Data, Engage SMEs*	*Automate Manual Inspections*	*Certify Improvements*	Reduces scrap and drives faster, data-backed process corrections on the floor
10. "Smart" Foundry			*Identify Foundry, Confirm KPIs*	*Retrofit Sensors, Pilot*	*Real-Time Monitoring, Predictive Maintenance, Quality Control*	Lifts uptime, yield, and safety, plus a replicable blueprint other foundries can adopt
11. "Smart" Forge Shop			*Identify Forge Shop, Confirm KPIs*	*Retrofit Sensors, Pilot*	*Real-Time Monitoring, Predictive Maintenance, Quality Control*	Lifts uptime, yield, and safety, plus a replicable blueprint other forge shops can adopt
12. Defense Digital Manufacturing Standards and Integration Program			*Define Machine-Readable Design File Standards*	*Automate Validation Tool*	*Interoperability Pilots with Foundries and Forge Shops* / *Scale*	Machine-readable standards and an automated validation pipeline that enable end-to-end model-based manufacturing across the DIB

Digital Fabric Roadmap Projects

Smart Factory and Automation | Workforce and Talent | Supply Chain and Production | Standards and Compliance



Digital Fabric Roadmap Projects

Smart Factory and Automation | Workforce and Talent | Supply Chain and Production | Standards and Compliance

Project Title	Timeline					Outcome
	FY26	FY27	FY28	FY29	FY30	
19. Supply Chain Risk Management Assessment of Raw Materials		Data Collection Finalized Report				Reduces supply risk and improves cost predictability for critical materials, while providing a blueprint for strategic partnerships and long-term supply
20. Time Study on MBE Impact for Production and Quality Systems			Current State Assessment Implement MBE Workflow	Future State Study		Quantifies the operational benefits of MBE adoption, accelerates qualification and production timelines, and builds a case for scaling MBE across suppliers
21. C&F Supply Chain Control Tower			Data Collection	Analyze NIIN-based specs Integrate AI/ML demand forecasting	Finalize Resource Platform	Reduces single-point failures – ensuring key components remain available even as demand or tariffs fluctuate
22. C&F Playbook for Model-Based Procurement		Discovery, Data Collection, Standards Mapping	Playbook Development, Pilot Finalization, Rollout, Governance			Reduces NRE costs and aligns suppliers to DOW-approved digital design and Model-Based Definition (MBD) workflows
23. "Open Specs" Technical Data Portal		Requirements, Governance, Security Architecture	Portal Development, Execute Multiple Pilots	Enterprise Rollout, Sustainment		Streamlines access to authoritative technical data, reducing bid cycle time and clarifying standards across DOW and industry
24. Digital Compliance Dashboard & Risk Monitoring Platform			Compliance Process, Requirements	Platform Development, Pilot Deploy		Automates tracking, reduces manual reporting burden, and improves audit readiness for C&F manufacturers

Appendix B – Research Topics

Pillar	Focus Area	Key Issues
Capacity	Capex & Opex Pressure	Rising maintenance overhead
		Legacy facility footprints limit efficiency
		Significant capital requirements for modernization
	Production Bottlenecks	Throughput limits restrict output
		Demand volatility drives inconsistent production levels
	Environmental & Zoning Constraints	Regulatory and geographic constraints
	Insufficient Large-Scale Facilities	Insufficient scaled, modern forging/casting capacity
	Unreliable Demand Signals	Mismatch between defense and commercial demand cycles
		Inaccurate demand forecasting
	Underutilized Capacity	Underutilized assets driven by short contract horizons
		Market misperception of underutilized U.S. capacity
	Supply Chain Complexity	Structural complexity creates timing gaps and inefficiencies
	Contracting Challenges	Prolonged, duplicative qualification processes
		Extended approval timelines for new suppliers/materials
	Compliance Burden	High-cost burden of MIL-SPEC/AS9100 compliance
		Excessive documentation and testing requirements
Supply Chain	Transparency Gaps	Limited visibility across multi-tier supply networks
		Quality and documentation inconsistencies
		Obsolete data practices complicate audits
	Component Lead Times	Extended lead times for critical components
		Scarce domestic options for large-format forgings
		Limited scalability in production
	Surge Capacity	Inadequate surge capacity for defense requirements
	Foreign Dependency	Dependence on foreign strategic materials
Technology	Adoption Barriers	Resource constraints and high integration complexity
		Organizational resistance to change
		Unclear investment returns
		Heightened cybersecurity risks
	Legacy Integration	Legacy systems hinder digital integration
		Non-standardized data and file structures
		Significant infrastructure modernization needs
		Gaps in data governance and quality control

	Data & Collaboration	Training gaps
		Cross-platform interoperability challenges
	Modeling & Data Challenges	High complexity in system integration
		High computational demands
		Constraints in advanced defect detection and optimization
	Compliance & Vulnerabilities	Stringent compliance frameworks for defense suppliers
		Strict cloud security impact-level requirements
		OT systems remain vulnerable
Workforce	Skilled Labor Gap	Acute skilled-labor shortages in advanced manufacturing
		Aging industrial workforce
		Intense talent competition across industries
		Declining industry attractiveness over time
	Visibility & Attraction	Low visibility among STEM pipelines
		Challenges attracting next-generation talent
		Looming competition from tech-centric industries
	Training Gaps	Underdeveloped technical training programs
		Gaps in apprenticeship pathways
		Limited continuing-education infrastructure
	Safety Concerns	Ongoing industrial safety exposures
		Risks from aging production equipment

Appendix C – Workshop 1 Materials

Appendix C1- Executive Summary: Workshop 1 (U.S. Casting and Forging Industry Challenges)

Workshop 1 (*Defining the Current State of C&F*) convened on November 4, 2025, with a diverse group of stakeholders from industry, academia, and government to identify and analyze the most critical challenges facing the C&F industry. The workshop consisted of 35 participants, who collaborated across four key focus areas—Capacity, Supply Chain, Technology, and Workforce—to identify challenges, rank priorities, and explore root causes. This summary serves as a foundation for internal planning and external engagement ahead of Workshop 2, which will focus on developing actionable solutions.

The workshop identified a complex array of systemic barriers that impede growth and modernization within the industry. Key challenges are depicted in the table below:

Category	Key Challenges
Capacity	• Insufficient and unpredictable demand signals • Material shortages • Untapped physical capacity • Insufficient downstream suppliers to effectively scale operations in response to demand • High operational and compliance costs
Supply Chain	• Scarcity of government incentives • Access to raw materials • Absence of end-to-end 3D digital files, compounded by complex compliance requirements, such as Cybersecurity Maturity Model Certification (CMMC)
Technology	• Slow adoption of digital technologies and data practices • Minimal use of data-driven decision-making • Low adoption of Industry 4.0 tools (digital simulation, ERP systems) • Fragmented technical data in outdated 2D formats • Concerns regarding intellectual property (IP)
Workforce	• Poor public image of industry • Aging labor force and cultural resistance to change • Weak training pipelines • Recruiting and retention issues

Root cause analysis pointed to several cross-cutting drivers, to include misalignment between procurement policies and industrial realities; societal and educational shifts away from trade careers; fragmented data standards; and a cost structure that disincentivizes modernization and investment due to high operational, material, financing, and compliance burdens.

Appendix C2- WS1 Slido Polls

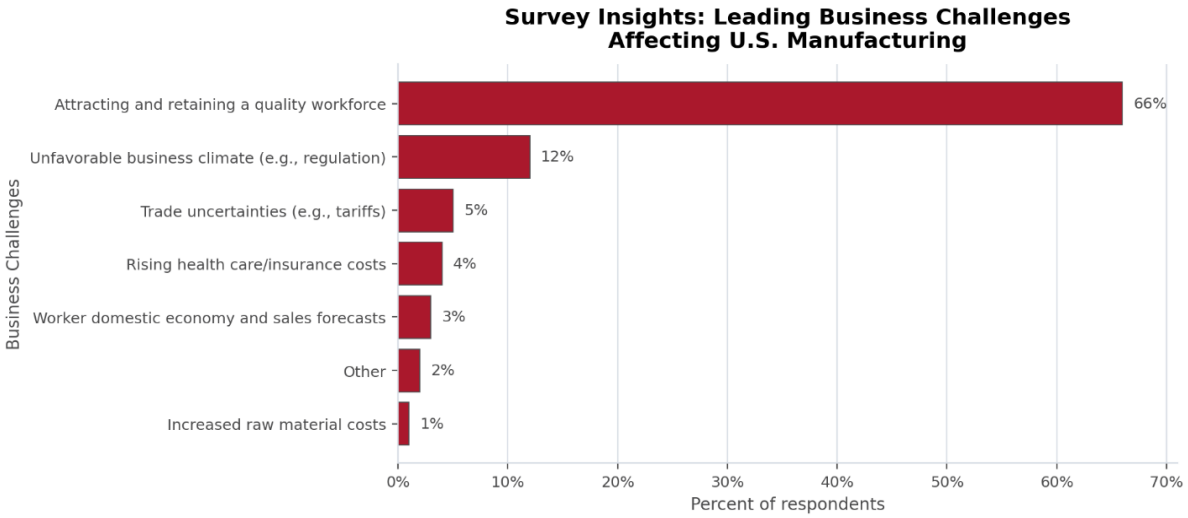


Figure 36. *Appendix C2 – Workshop 1-Slido Results (1 of 4)*

Figure 36 shows that, during Workshop 1, the team reviewed survey results to inform discussions on workforce growth strategies from other industries and their relevance to the DIB. The analysis also examined how factors such as trade uncertainty and tariffs affect manufacturing conditions and workforce challenges within the DIB.

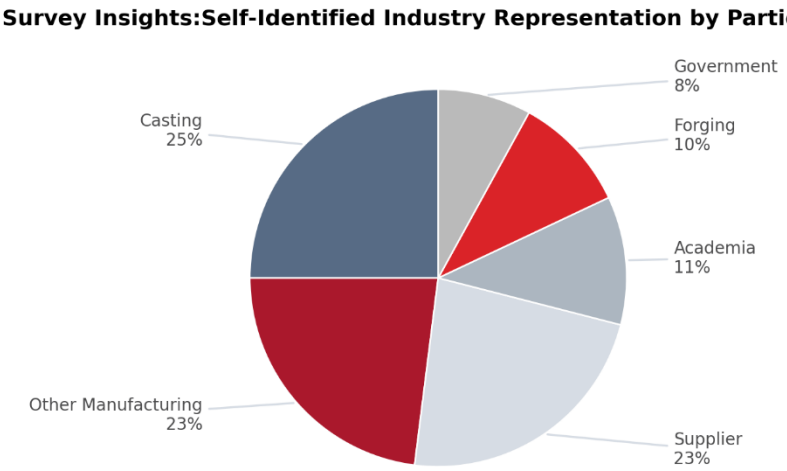


Figure 37. *Appendix C2 – Workshop 1 – Slido Results (2 of 4)*

Figure 37 summarizes the results of a Slido survey conducted during Workshop 1, in which participants voluntarily self-identified the industry they represent.

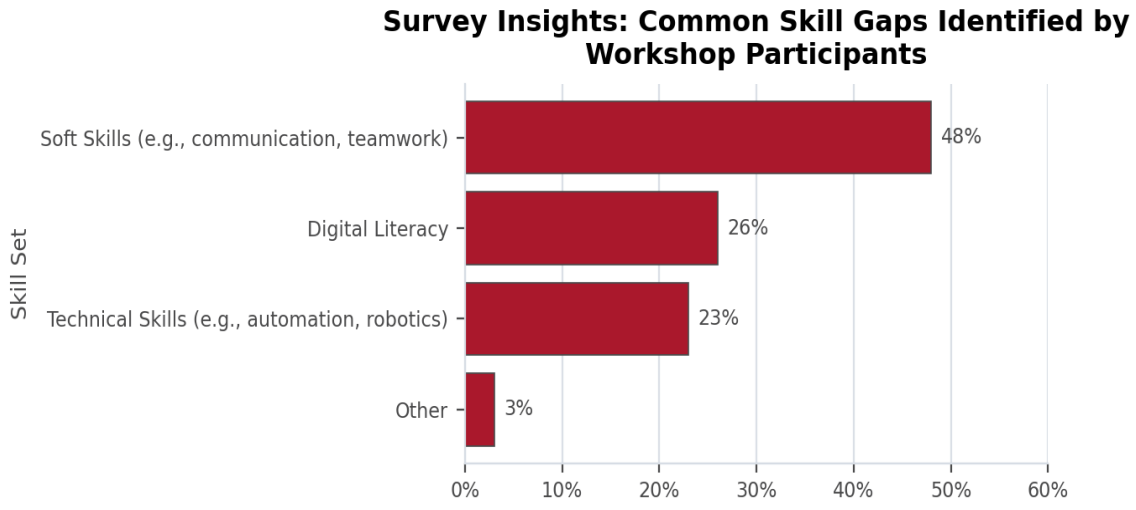


Figure 38. *Appendix C2 - Workshop 1-Slido Results (3 of 4)*

Figure 38 shows that soft skills represent the most significant gap identified in the Workshop 1 survey results, with digital literacy and technical capabilities such as automation and robotics cited less frequently. The findings suggest that workshop projects focus on digital communication, teamwork, and targeted skill development aligned with DIB requirements.

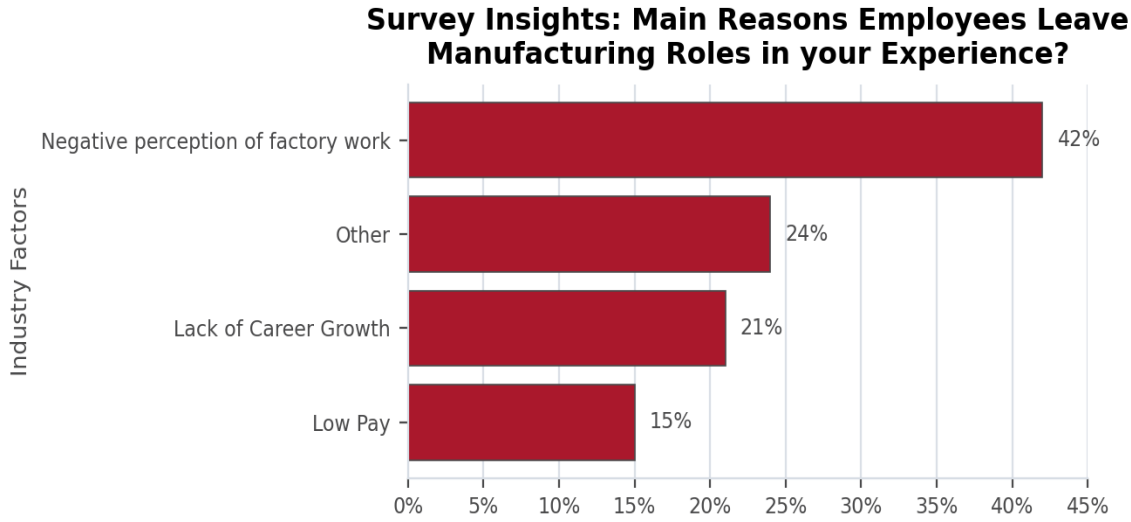


Figure 39. *Appendix C2 - Workshop 1-Slido Results (4 of 4)*

Figure 39 shows that, in Workshop 1, survey responses point to negative perceptions of factory work as the leading contributor to employee attrition, outweighing factors such as career progression and compensation. The results highlight the value of cross-industry workforce benchmarking and focused branding efforts aimed at improving perceptions of manufacturing roles and supporting retention.

Appendix C3 – WS1 Summary of Pain Points by Category

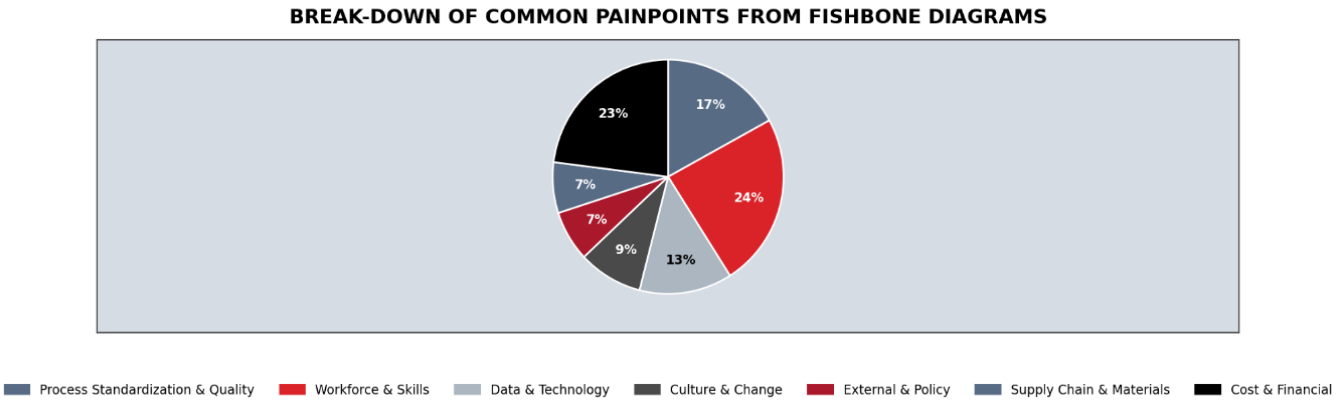


Figure 40. *Workshop 1 Summary of Pain Points by Category*

The figure above summarizes the analysis results. After reviewing all groups' fishbone diagrams, the team applied a normalization process to identify and organize issues into seven primary themes.

Appendix C4 – Problem Statements (created as output workshop)

Casting & Forging Problem Statements
1. **Working with DOW**: Complex DOW procurement processes/timelines, strict product specifications, and end-item purchasing method create obstacles for industry participation
2. **Skilled Workforce Gaps**: Shortage of qualified workers within the DIB C&F industry limits capacity, innovation, and readiness to meet DOW requirements
3. **Unreliable Demand Signals**: Poorly forecasted DOW demand and funding streams lead to underutilized capacity
4. **High Costs & Limited Capital**: Investment required to meet DOW prototype specifications and limited capital to produce small production runs limits the C&F industry's ability/desire to answer RFPs
5. **Technology & Data Shortfalls**: limited analytics and resistance to automation hinder modernization and efficiency
6. **Lack of End-to-End Digital Design Files**: Government-provided digital files do not always follow current industry standards; lack of 3D digital files slows design collaboration and increases rework, increasing the cost and reducing speed to market
7. **Legacy Equipment Bottlenecks**: Aging machinery causes frequent breakdowns and delays; long lead times for replacement parts stall operations, which increases downtime costs and limits the industry's ability to scale or meet DOW timelines
8. **Negative Perception of Manufacturing Work**: Potential new entrants to the field have a negative view of C&F or are underexposed to the industry, which reduces

talent inflow and worsens workforce shortages, limiting long-term growth and innovation
9. **Heavy Compliance Burden**: Complex requirements inherent in CMMC, stringent environmental regulations, and OSHA policies increase administrative workload and present a significant barrier to competing for DOW contracts
10. **Lack of Training and Apprenticeship Programs**: Insufficient nationwide programs hinder skill development and workforce growth; compounded by lack of journeymen level trainers
11. **Raw Material Sourcing & Tariffs**: Scarcity of raw materials (e.g. rare earth, not found domestically, etc.) needed for C&F production and cost uncertainty make production costly or impossible
12. **Resistance to Change/Cultural Inertia**: Fear of redundancy and perceived system complexity drive employee resistance and delay technology adoption, leaving the industry less competitive
13. **Lack of Industry-Wide Standards**: DOW does not always solicit bids or provide information based upon the latest industry standards or practices (e.g., using paper sketches instead of CAD), leading to high upfront non-recurring costs, which are not reimbursable under the current acquisition schema

Appendix C5 – WS1 Key Themes and Signature Issues in C&F

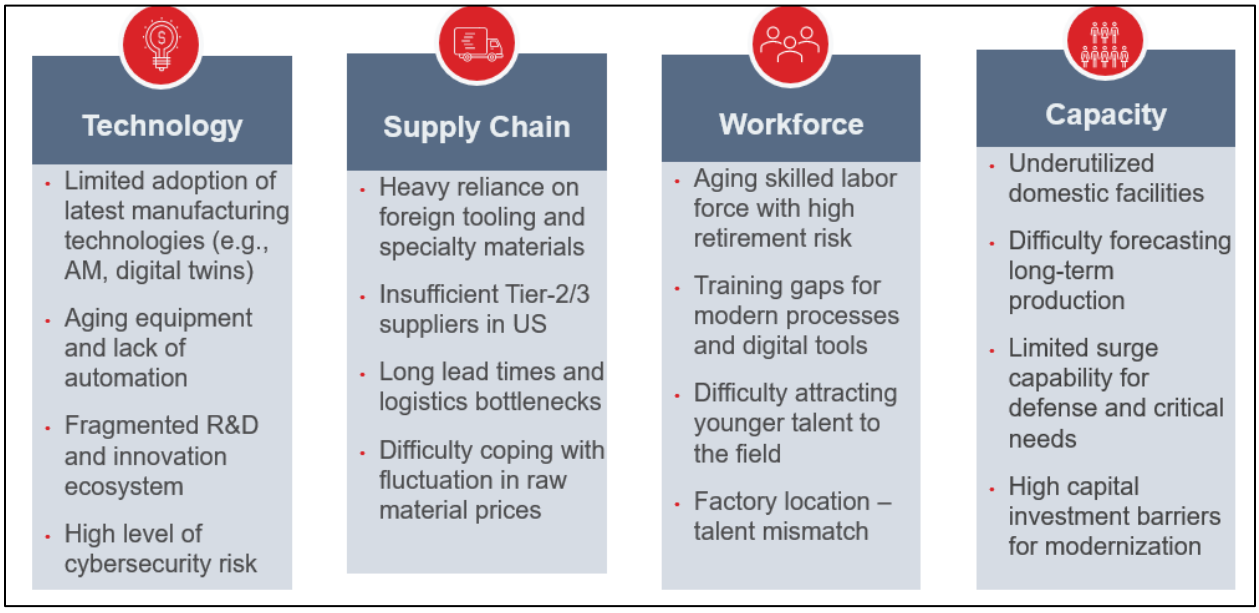


Figure 41. *Workshop 1 Key Themes and Signature Issues in C&F*

Appendix C6 – WS1 Insights Mapping of Cross Cutting Challenges

Challenge	Supply Chain	Capacity	Technology	Workforce
1. Government DOW Barriers	■	■	■	
2. Skilled Workforce Gaps	■	■	■	■
3. Unreliable Demand Signals	■	■	■	
4. High Costs & Limited Capital	■	■	■	
5. Technology & Data Shortfalls		■	■	■
6. Lack of End-to-End Digital Files		■	■	
7. Legacy Equipment Bottlenecks	■		■	
8. Negative Perception of Manufacturing		■		■
9. Compliance Burden (ex: CMMC,OSHA)	■	■		
10. Drug Testing & Screening Barriers		■		■
11. Lack of Training & Apprenticeship Programs			■	■
12. Raw Material Sourcing & Tariffs		■	■	
13. Resistance to Change / Cultural Inertia			■	■
14. Manual Backend Processing			■	
15. Lack of Industry-Wide Standards		■		
16. Limited Recyclable Materials		■		

Appendix D – Workshop 2 Materials

Appendix D1- Executive Summary: Workshop 2 (U.S. Casting and Forging Industry Actionable Solutions)

Workshop 2 (*Understanding Potential Solutions to Advance Casting & Forging through Digital Manufacturing*) took place on December 9, 2025, bringing together stakeholders from diverse segments of the C&F industry. Participants included representatives from government, specifically the DOW, academia, and manufacturing organizations ranging from small businesses to large enterprises. The team developed this workshop to build upon the insights of Workshop 1 (*Defining the Current State of C&F*) and develop actionable solutions for the C&F industry, to support the DIB. 31 participants attended this workshop to collaborate on key challenges that were identified from Workshop 1. This summary serves as a foundation for internal planning and external engagement ahead of Workshop 3, which will focus on creating a cohesive C&F Technology Roadmap to guide the industry's future.

The workshop identified strategic recommendations for strengthening the C&F industry, organized across short-term (zero to one year), mid-term (one to three years), and long-term (three or more years) timelines. The table below highlights potential solutions aligned to the key themes discussed during the workshop:

Themes	Potential Solutions
Need for Partnership	• Establish multi-year IDIQ/offtake contracts to anchor demand and mitigate risk • Create joint DOW-industry governance bodies for standards oversight
Combining Tech & Talent	• Launch Onramp programs to capture retiree knowledge and mentor new workers • Deploy Augmented Reality (AR)-assisted training and vendor-supported equipment certifications
Data-Driven Future	• Convert legacy 2D drawings to model-based digital Technical Data Packages (TDPs) • Build out industry-wide data lakes to enable shared AI model development
Cultural Workforce Shift	• Run national PR campaigns with influencer-backed scholarships and youth outreach • Reintroduce shop classes and vocational tracks in K-12 educations

Appendix D2 – WS2 Mapping Solutions to Identified Problem Statements

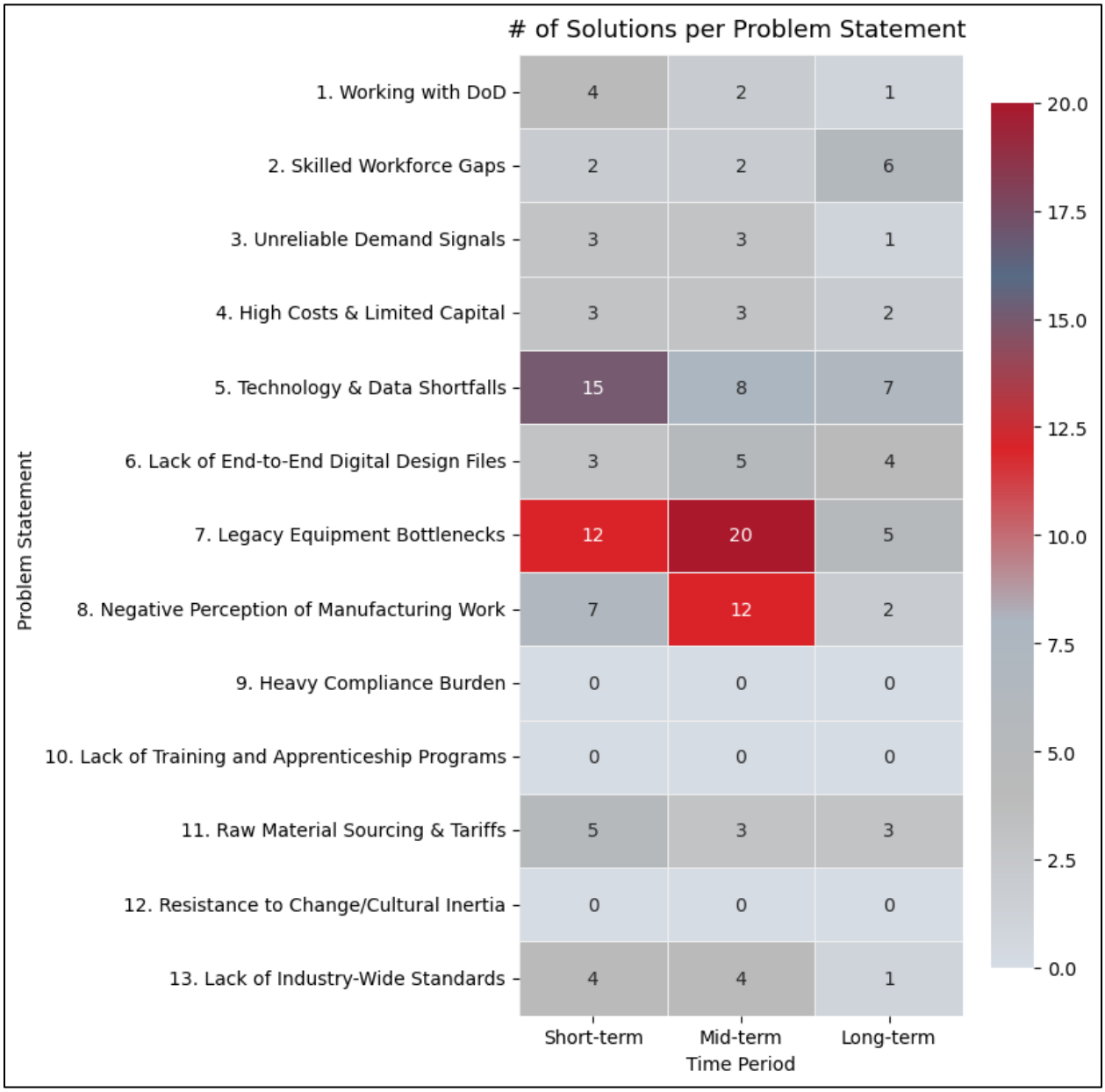


Figure 42. *Workshop 2 Mapping Solutions to Identified Problem Statements*

Appendix D3 – WS2 Breakout 2 Solution Identification Template

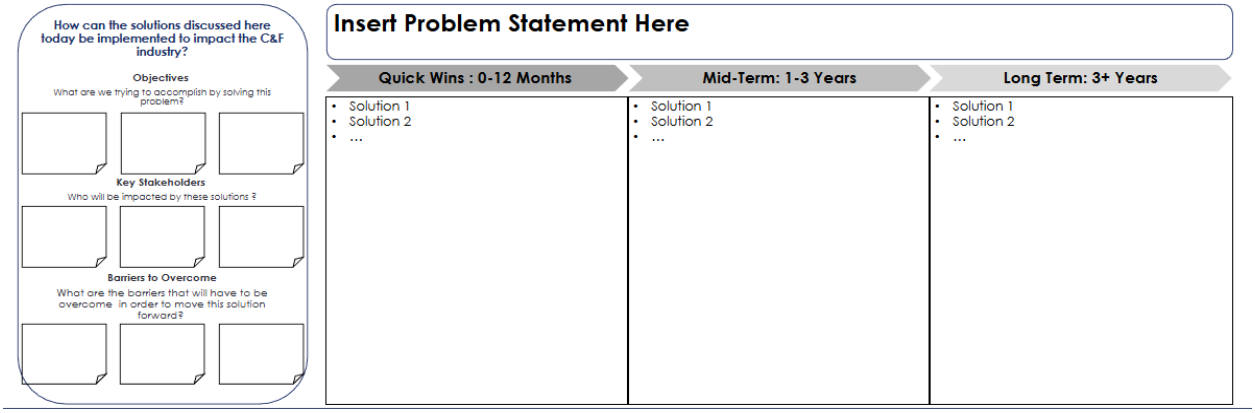


Figure 43. *Workshop 2 Breakout 2 Solution Identification Template*

Appendix E – Workshop 3 Materials

Appendix E1- Executive Summary Workshop 3 (Validating Input for the Digital Manufacturing Roadmap for the U.S Casting & Forging)

Workshop 3 (Validating Input for the Digital Manufacturing Roadmap) convened on January 21, 2026, bringing together a diverse group of stakeholders from industry, academia, and government to review, assess, and refine the inputs for the proposed digital manufacturing roadmap for the Casting and Forging (C&F) industry. The workshop included 22 participants, who evaluated the roadmap's priority initiatives and provided targeted feedback across the four strategic focus areas—**Smart Factory & Automation, Workforce & Talent, Supply Chain & Production, and Standards & Compliance.**

This final workshop was built on the outputs of Workshops 1 and 2, serving as the culminating step in validating project concepts, identifying implementation considerations, and ensuring alignment between industry needs and the proposed modernization strategy. The session generated actionable insights:

Category	Summary of Actionable Insights
Smart Factory and Automation	• **Data-First Implementation Approach**: Prioritize data maturity and operational readiness before pursuing advanced technologies such as AI, enabling a more practical and sustainable modernization path. • **Digital Readiness**: Support phases digital transformation through industrial-grade sensing, standardized data frameworks, and interoperability-focused architectures that deliver reliable insights. • **On-Floor Analysis**: Conduct on-floor and workflow analysis prior to full platform development. Standardize data formats and incorporate research partnerships to support phased digital-twin development. • **Investment Focus**: Consolidate overlapping initiatives to prioritize investments in solutions that demonstrate clear ROI, simplified integration, and value demonstrated across both casting and forging operations.
Workforce and Talent	• **Credentialed Training**: Expand hands-on training programs that upskill workers and offer portable, industry-aligned credentials. • **Digital Skills in Education**: Integrate digital skills into manufacturing education through partnerships and modern training methods, such as gamified and mobile learning. • **Recruitment Strategies and Job Awareness**: Increase awareness of casting and forging jobs by showcasing technology-enabled workplaces and linking training to real career pathways. • **Structured Playbook Development**: Utilize academic, community programs, and trade associations to create a structured, user-friendly playbook that accelerates digital manufacturing adoption in casting and forging environments.
Supply Chain and Production	• **Supply Chain Transparency & Digital Integration:** Align with existing DOW systems to enhance supply chain transparency and reduce complexity (DLA and Service platforms, e.g., ICON). • **Equitable Access for Small and Mid-Sized Manufacturers:** Simplify participation for small and mid-sized manufacturers to promote fair access and reduce administrative burdens.

	• **Coordinated, Multi-Tier Forecasting for a Resilient Materials Strategy:** Incorporate DOW demand-signal forecasting, assess second- and third-order materials, and integrate regional supplier metrics for a comprehensive raw materials strategy.
Standards and Compliance	• **Cyber-Ready Technical Data Portal Modernization**: Strengthen the centralized technical data and Q&A portal by establishing a clear cyber/CMMC compliance posture, integrating DLA/Acquisition Streamlining & Standardization Information System (ASSIST) resources. • **Strengthened Governance Through Early, Cross-Stakeholder Collaboration:** Strengthen governance and adoption through early collaboration (DLA, primes, PLM/CAD vendors, standards bodies) and practical playbooks, portals, and training.

As next steps, MxD and its partners incorporated the feedback from Workshop 3 into the **Digital Manufacturing Roadmap for the Casting and Forging Industry**. The final roadmap will be shared with participants and stakeholders upon publication.

Appendix E2 - WS3 - Breakout 1 Insights – Sample Project Poster

P16: Workforce Mapping and Regional Talent Assessment for C&F *Estimated Timeline: 6 months*	**Category** Workforce and Talent **Problem Statement(s)** 2 **Solution(s)** 2.3
Project Description: Analyze regional labor markets and skill availability using data, employer input, and geospatial tools to identify talent gaps and align training investments with the actual C&F workforce needs. **Focus Areas** • Mapping regional skill supply and demand. • Identifying talent gaps and training needs. • Informing workforce strategy and investment. **Approach** • Use labor data and employer interviews and geospatial analytics to map skills. • Identify regional gaps and strengths and assess job-demand alignment. • Provide insights to guide training programs and policy recommendations.	
Value Delivered	**Performance Indicators**
1. Enabled data-driven workforce planning for C&F regions. 2. Supported alignment of training programs with labor-market needs. 3. Strengthened regional talent pipelines for modernization.	• # of regions analyzed • # of high-priority skill gaps identified • Top skill gap per region
Project Improvement Suggestions	
Inputs from participants during WS#3- Breakout #1	

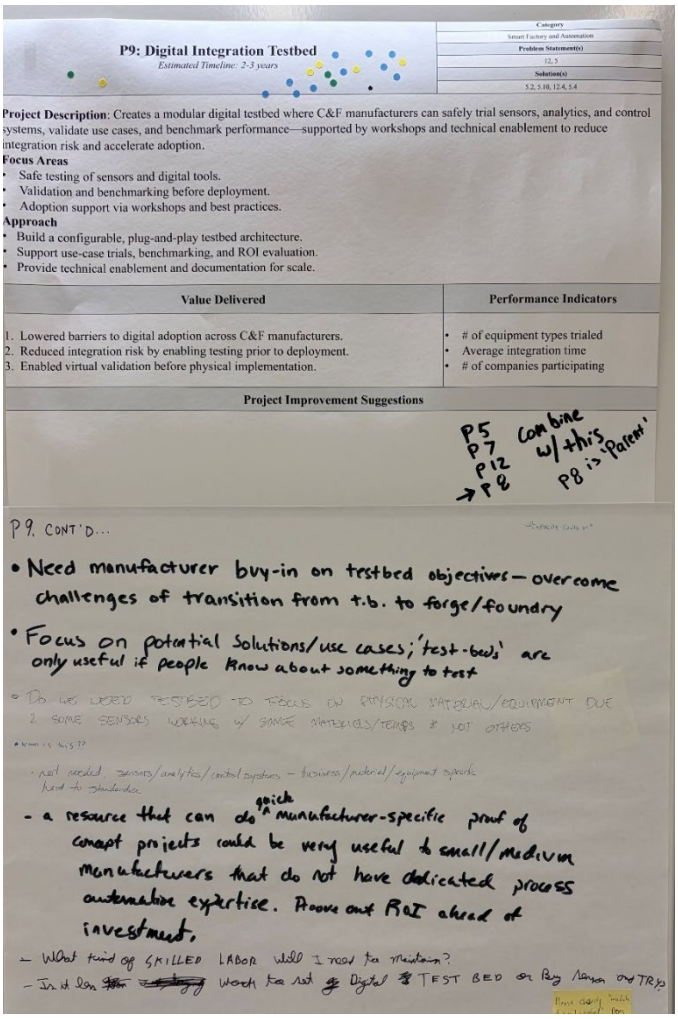
Figure 44. *Workshop 3 Sample Project Poster*

Appendix E3 – WS3 – Breakout 2 Insights – Project Overview Template

<table>
<tr><th colspan="4">P1: Supply Chain Risk Management Assessment of Raw Materials</th></tr>
<tr><th colspan="4">Key Activities</th></tr>
<tr><td colspan="4">Inputs from participants during WS#3- Breakout #2</td></tr>
<tr><th colspan="4">Identify Recommended Phases</th></tr>
<tr><td colspan="2" rowspan="2"></td><th colspan="2">Timeline</th></tr>
<tr><td></td><td></td></tr>
<tr><th colspan="2">Value Delivered</th><th colspan="2">Performance Indicators</th></tr>
<tr><td colspan="2">1. Reduces supply risk and improves cost predictability for critical materials.
2. Strengthens supply chain resilience and national security for DoD and industry.
3. Provides a blueprint for strategic partnerships and long-term supply agreements.
4.
5.
6.</td><td colspan="2"># of Alternative Suppliers Identified
Supply Risk (%)
Supply Risk Improvement (%)
Cost Reduction (%)</td></tr>
<tr><td>Dependencies</td><td></td><td>Risks</td><td></td></tr>
</table>

Figure 45. *Workshop 3 Project Overview Template*

Appendix E4 – WS3 – Key Stakeholder Feedback Highlights from Project Posters



P9: Digital Integration Testbed

Estimated Timeline: 2-3 years

Category
Smart Factory and Automation
Problem Statement(s)
12, 5
Solution(s)
5.2, 5.10, 12.4, 5.4

Project Description: Creates a modular digital testbed where C&F manufacturers can safely trial sensors, analytics, and control systems, validate use cases, and benchmark performance—supported by workshops and technical enablement to reduce integration risk and accelerate adoption.

Focus Areas

- Safe testing of sensors and digital tools.
- Validation and benchmarking before deployment.
- Adoption support via workshops and best practices.

Approach

- Build a configurable, plug-and-play testbed architecture.
- Support use-case trials, benchmarking, and ROI evaluation.
- Provide technical enablement and documentation for scale.

Value Delivered	Performance Indicators
1. Lowered barriers to digital adoption across C&F manufacturers. 2. Reduced integration risk by enabling testing prior to deployment. 3. Enabled virtual validation before physical implementation.	• # of equipment types trialed • Average integration time • # of companies participating

Project Improvement Suggestions

P5 P7 P12 → P8 Combine w/ this P8 is 'Parent'

P9. CONT'D...

- Need manufacturer buy-in on testbed objectives – overcome challenges of transition from t.b. to forge/foundry
- Focus on potential solutions/use cases; 'test-beds' are only useful if people know about something to test

- Do we need testbed to focus on physical material/equipment due 2. some sensors working w/ some materials/temps & not others

- need needed sensors/analytics/control systems – business/material/equipment specific hard to standardize

- a resource that can do quick manufacturer-specific proof of concept projects could be very useful to small/medium manufacturers that do not have dedicated process automation expertise. Prove out ROI ahead of investment.

– What kind of skilled labor will I need to maintain?

– Is it low ~~effort~~ worth to set up Digital & TEST BED or Big Savings on TRL?

Figure 46. *Workshop 3 Key Stakeholder Feedback Example*

Appendix E5 – WS3 – Frequency of Key Themes in Stakeholder Feedback

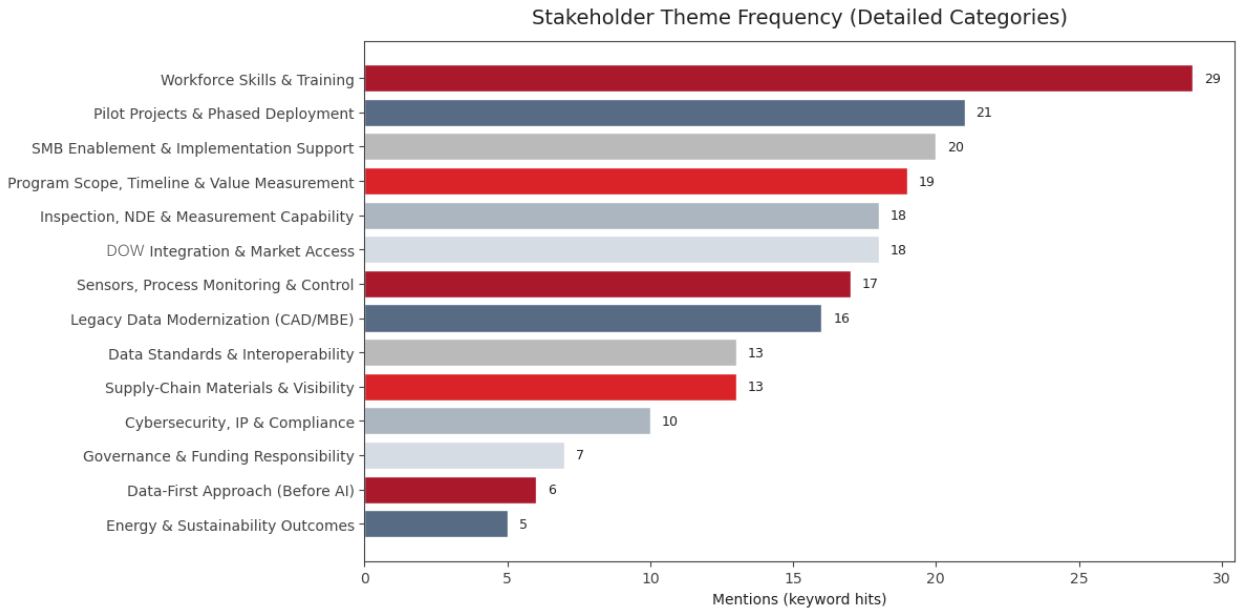


Figure 47. *Frequency of Stakeholder Feedback Key Themes from Workshop 3*

Appendix F – Roadmap Development Stakeholders

Appendix F1 – Workshop Participants Across all Workshops

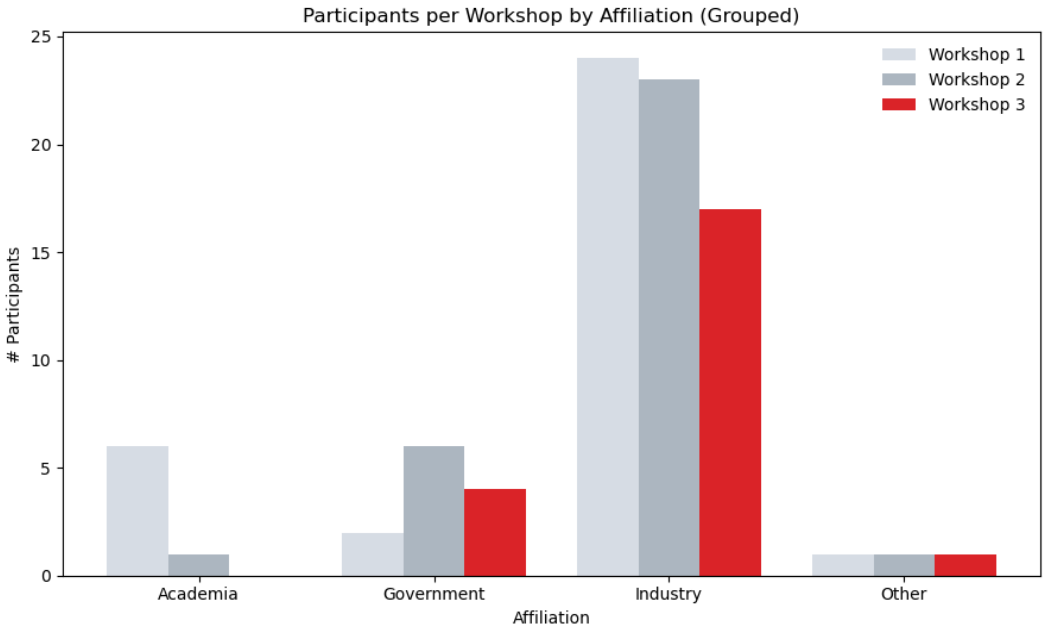


Figure 48. Participant Affiliation Across Workshops

Appendix F2 – Participants Affiliation Across all Workshops

MxD						**Project Team**
Oak Ridge National Laboratory	JMTC / Rock Island Arsenal / US Army Ground Vehicle Systems Center	Bechtel Plant Machinery, Inc	Cook County Government / Bureau of Economic Development	Air Force Research Lab	Sen. Tammy Duckworth Office	**Government**
The Ohio State University / CMDE	University of Northern Iowa Metal Casting Center	University of Illinois-Manufacturing Institute	Purdue University	Northwestern University		**Academia**
PowderCoil Technologies Center Tool Company Fabri Inc. Blue Forge Alliance	American Foundry Society Skuld LLC Lockheed Martin Jobs for the Future	Ignitia-ai Howmet Aerospace Rangeview SME	Kunkel-Wagner GmbH Germany BCD iLabs Inc. Non-Ferrous Founders' Society PDA LLC	ARM Institute ARIS Technology America Makes/NCDMM ARCTOS Technology Solutions, LLC	Scot Forge Company Concurrent Resources LLC PROMESS First Principals Management H.A Burrow Pattern Works Inc.	**Industry and Professional Associations**

Appendix G – Communications and Marketing Methods Deployed

Appendix G1 – Sample Email Communication

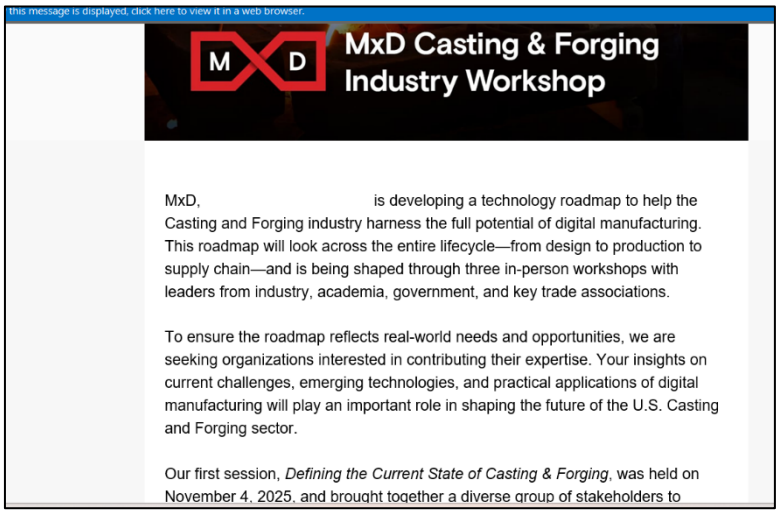


Figure 49. *Sample Email Communication*

Appendix G2 – Sample Social Media Communication

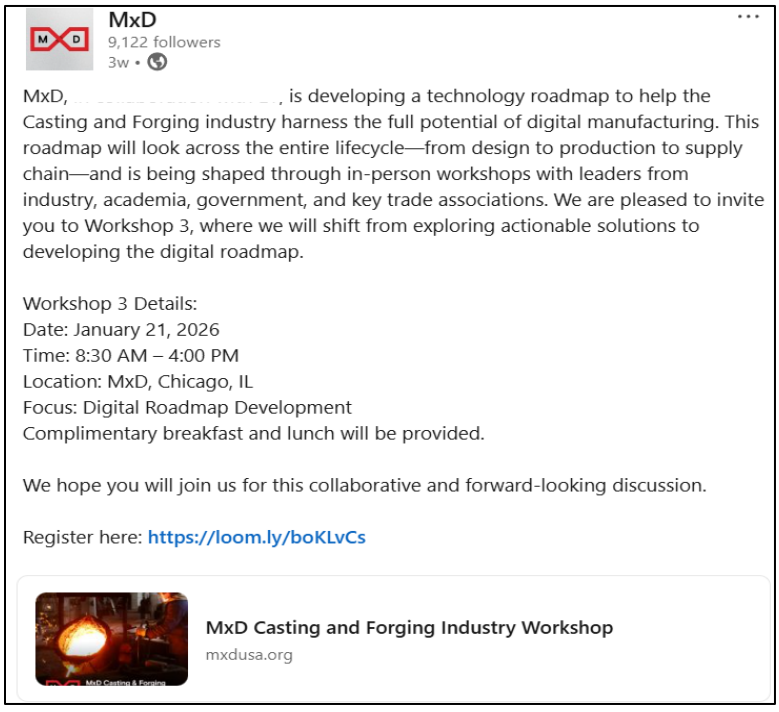


Figure 50. *Sample LinkedIn Post*

Appendices G1 and G2 provide representative samples of the approach used to effectively engage industry leaders and key stakeholders. MxD implemented a targeted LinkedIn marketing campaign leveraging its network of approximately 9,000 followers, in addition to deploying a targeted email campaign reaching approximately 140 industry leaders and stakeholders.

Appendix H – Glossary of Acronyms

Acronym	Definition
AFRL	Air Force Research Laboratory
AFS	American Foundry Society
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
ARM	Advanced Robotics for Manufacturing (Institute)
AS9100	Aerospace Quality Management Standard
ASSIST	Acquisition Streamlining & Standardization Information System
C&F	Casting & Forging
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CapEx	Capital Expenditure
CFR	Code of Federal Regulations (appears in OSHA citation in body)
CMMC	Cybersecurity Maturity Model Certification
DIB	Defense Industrial Base
DLA	Defense Logistics Agency
DOW	Department of War
ERP	Enterprise Resource Planning
FIA	Forging Industry Association
IBAS	Industrial Base Analysis and Sustainment Program
IT/OT	Information Technology / Operational Technology
KPI	Key Performance Indicator
MES	Manufacturing Execution System
MII	Manufacturing Innovation Institute
MILSPEC	Military Specification
NADCAP	National Aerospace and Defense Contractors Accreditation Program
NCDMM	National Center for Defense Manufacturing & Machining
OEM	Original Equipment Manufacturer
OpEx	Operating Expenditure
OSD	Office of the Secretary of Defense
OT	Operational Technology
PLM	Product Lifecycle Management
ROI	Return on Investment
SFSA	Steel Founders' Society of America
SMB(s)	Small and Mid-Sized Business(es)
SME	Subject Matter Expert
TDP / TDPs	Technical Data Package(s)

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