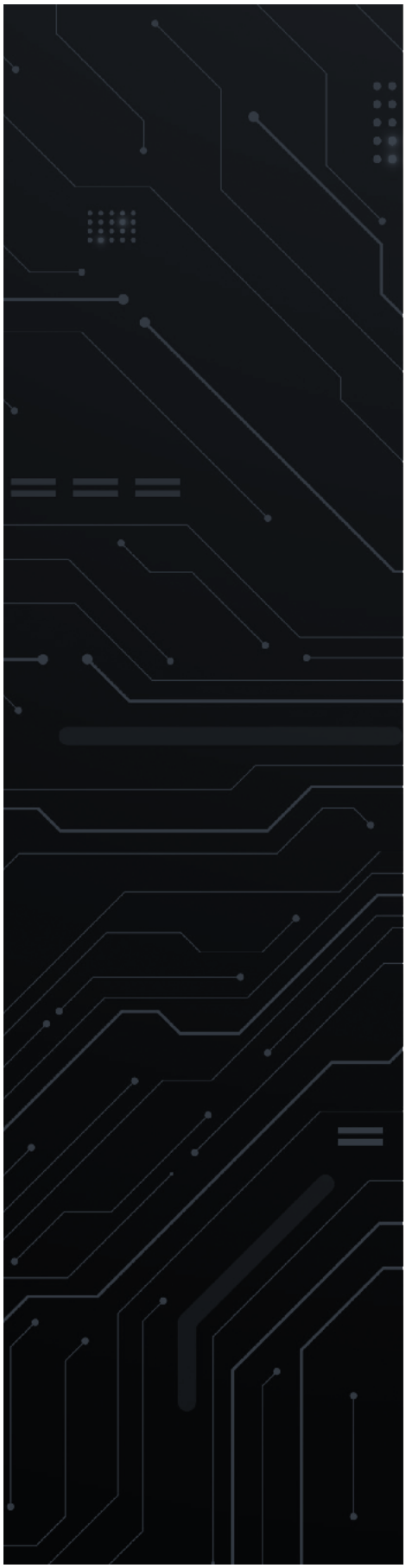

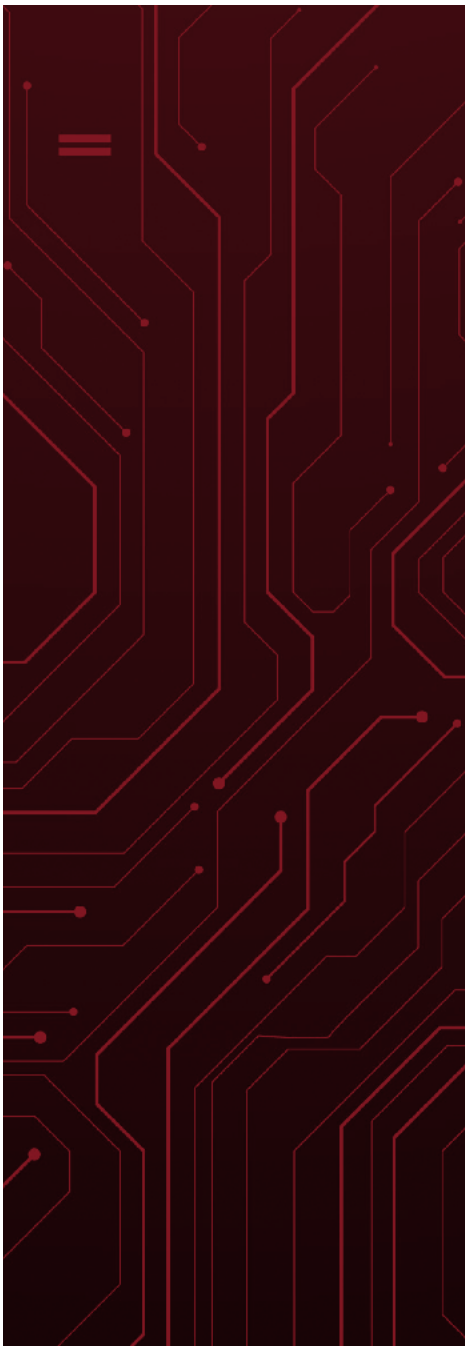

The Digital Manufacturing & Cybersecurity Institute

STRATEGIC INVESTMENT PLAN 2025-2027

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Acknowledgment

The SIP is developed in collaboration with MxD's member organizations including manufacturers, solution providers, academics, nonprofits, and the Department of Defense partners. They represent a cross section of manufacturing that together forms a robust public-private partnership committed to an innovative and thriving U.S. manufacturing sector. We are especially grateful to the insights and leadership of the MxD Technical Advisory Committee and Executive Council members.

As we celebrate over a decade of delivering on our mission to strengthen U.S. manufacturing competitiveness, we extend a special thank you to some of our founding members who continue to actively engage today: Boeing, Dow, Lockheed Martin, Rolls-Royce, Siemens, Georgia Institute of Technology, University of Illinois, Purdue University, and Rochester Institute of Technology.

MxD seeks to engage distinct and sometimes disparate stakeholders toward a common goal, and the SIP reflects that spirit of collaboration.

Confidentiality

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Message from the CEO

Dear MxD Community,

As the nation's Digital Manufacturing and Cybersecurity Institute, MxD was launched with a mission to support the U.S. industrial base at a time of increased global competition and fast-moving technological advancements.

Since then, the manufacturing sector has faced an extraordinary array of challenges and changes, from stresses on supply chains to the rise of artificial intelligence. Given that industry will face disruption as technology advances at an ever-accelerating pace, manufacturers must have the ability to meet demand and protect against cyberattacks. Likewise, the Department of Defense must improve the resilience of the Defense Industrial Base in an era of increasing global conflict risk.

In collaboration with a network of manufacturers, solution providers, academics, and government partners, MxD continues to meet the moment by serving as a critical resource in driving impact at scale and creating opportunities to advance U.S. manufacturing by:

- Convening the industrial base to identify and solve key challenges that manufacturers face in modernizing and securing their operations
- Advancing technology innovation and digital adoption to deliver resilient and revitalized supply chains
- Empowering the workforce with the skills necessary to meet industry's current and future needs

With input from our members and our broader partner base, we've updated this year's Strategic Investment Plan (SIP) to build on our past contributions by providing a detailed roadmap for our 2025–2027 priorities. The SIP identifies key digital manufacturing priorities that reinforce the need for manufacturers to work collaboratively as members of supply chains by improving data flow, management, and governance. At both the enterprise and external levels, upskilling the workforce and implementing cybersecurity best practices are critical in delivering a successful digital transformation.

We will continue to prioritize projects and proposals designed to meet the evolving needs of the industrial base, relying on your insights and involvement throughout. Our collaborative approach has proven to be effective during MxD's first decade and continues to be the model driving this SIP and MxD forward.

Thank you for your commitment and contribution to our mission!

All the best,

Berardino Baratta
CEO, MxD

Executive Summary

The United States must have a vibrant, modern manufacturing base to bolster the economy and protect national security. This demands continued investments and upgrades in digital capabilities by industry, government, and academia.

MxD, the nation's Digital Manufacturing and Cybersecurity Institute, collaborates with manufacturers, solution providers, academics, and government partners to accelerate digital innovation and adoption. Since the institute's inception eleven years ago, we have delivered value to our membership by understanding its needs and bridging technology gaps. As we continue to drive impact at scale, MxD's goals are primarily focused on:

- Digitalizing and helping secure ten thousand manufacturers
- Upskilling one million workers
- Supporting the Department of Defense's efforts to build a modern and resilient Organic Industrial Base (OIB)

To achieve these targets by 2028, MxD must scale available programs for an increasing number of U.S. manufacturers. The faster manufacturers advance their digital capabilities, the more prosperous and secure the manufacturing base — and the nation — will become.

Despite its vital contributions to the economy and national defense, the manufacturing base faces constant challenges in its efforts to improve productivity, develop the workforce of the future, and defend against cyberattacks. The struggles are particularly acute for the nation's small and medium manufacturers (SMMs), which have limited resources to research and invest in the latest secure digital technologies and skilled workers. Between 2010 and 2020, the United States lost 20,000 manufacturers, nearly all small manufacturers. Without clear guidance and resources for digital adoption, they will be unable to compete effectively.

Digital manufacturing matters because it enhances operational efficiency and fosters a collaborative environment where transparency and communication are prioritized. As a result, companies can respond swiftly to market demands, optimize resource allocation, and ultimately deliver higher-quality products to customers and consumers more efficiently, creating an extremely resilient and adaptable supply chain.

With the release of our latest Strategic Investment Plan (SIP), MxD is poised to build on the progress made over the past decade. Influenced by the continuous engagement and understanding of the priorities of the industrial base, the SIP outlines roadmaps for the next three years (2025–2027) to address the most critical needs in U.S. manufacturing and leverage the advancements in digital technologies, computing power, connectivity, and enhanced analytics.

With the input of manufacturers, solution providers, government, and academia, we are committed to achieving our goals by helping develop a modern workforce, embrace key digital technologies, and secure operations from cybersecurity threats.

MxD's technology strategy utilizes a data-driven approach to advance capabilities in three primary areas: digital

engineering and design, the future factory, and the supply chain. Forward-looking initiatives and research are also pursued to keep pace with emerging technologies for manufacturing (i.e., digital twins, artificial intelligence, 5G/6G). We focus our efforts within the product life-cycle framework, defined as develop, make, deploy, and support.

Our network has shared that barriers still exist and a recurring challenge is the quality and fidelity of data as members look to scale solutions across their enterprises and supply chains. The curation of clean, actionable data can be broken down into several components: data flow, data management, and data governance.

Data flow is the thread that links people, processes, and technology within a supply chain. The seamless movement of this data is essential to unlock the benefits of digital manufacturing. This implies trust in data sharing and compatibility within enterprise departments, throughout an enterprise, and between enterprises. Data management and data governance have become fundamental components in effectively executing a digital adoption strategy.

MxD continues to evaluate current and future projects that address challenges and/or provide manufacturing solutions. Digital adoption will not occur without a solid methodology demonstrating how to take advantage of the lessons learned and apply available technologies in an existing operation to deliver immediate value.

Understanding and addressing these challenges as related to a framework we refer to as the “data lifecycle” is critical to nurturing a robust and competitive manufacturing base in the United States. The past five years have demonstrated how easily disrupted global supply chains can become, compelling manufacturers to become more resilient and adaptable. The pandemic upended supply chains, while the invasion of Ukraine put significant stress on the Defense Industrial Base, including the OIB. The entire manufacturing base has become a significant daily target for cyberattacks.

This SIP provides a three-year outlook on how MxD plans to scale our impact across U.S. manufacturers in a way that will provide value to small and large manufacturers alike and establish the necessary supply chain that will be ready for future demands. MxD recognizes this challenge as a call to action for digitalized industrial mobilization for the national industrial base.

The SIP contains specific programs and proposals for helping organizations develop digital prowess, explore new manufacturing techniques, and support workforce training.

Investments in digital technologies will be part of what makes the difference between an America that is vulnerable, or one that is strong and secure.

MxD's Strategic Investment Focus

MxD's CTO Strategy: Data as a Foundational Approach

Advances in manufacturing technology are happening at an accelerating pace. These advances are driven by improved computing power, increased connectivity, and enhanced analytics. However, this pace of advancement brings growing disparities within the U.S. manufacturing base between those with the resources to leverage these advances and those without. The latest census data indicates that 74% of U.S. manufacturing firms are small having 20 employees or fewer.[1] Between 2010 and 2020, the United States lost 20,000 manufacturers, of which nearly all were small manufacturers. Small and medium manufacturers (SMMs) are at the most risk of losing competitiveness as they struggle to adopt digital manufacturing. Their struggle has been compounded by the collapse of the supply chain during the COVID-19 pandemic, a shortage of skilled workers, and the manufacturing sector being the most targeted by cybersecurity attacks globally since 2022.

Challenges in digital adoption are not limited to SMMs. In 2024, the Manufacturers Alliance Foundation in collaboration with Siemens USA published *Digitalization Gains: Manufacturers Forge Ahead with Digital Transformation.*[2] Of the nearly 200 executives from mid-cap to large-cap manufacturing companies in the United States interviewed for the report, 80% had implemented or were implementing digitalization for various purposes. The areas most targeted for digitalization were supply chain optimization, product planning and development, manufacturing/production efficiency/overall equipment efficiency (OEE), data analytics, business intelligence, inventory and warehouse management, and after-market services optimization.

These leaders also highlighted challenges such as measuring return on investment (ROI), lack of alignment between functions, and inefficient use of data and analytics. The report noted that when organizations lack a comprehensive digital strategy across their internal enterprise and supply chain, gaining an impactful competitive advantage from digital adoption could not be fully realized. Companies that took a more systematic approach, merging their digitalization roadmap with a business case for moving forward and implementing effective change management, have made the most technological advancements. This underscores the role of change management and industry collaboration in digital adoption and the importance of trust and data sharing across organizations.

The key to successful digital adoption rests with manufacturers understanding two points: 1) their current digital maturity and 2) what business solutions they seek by leveraging digital manufacturing capabilities. Having an understanding of the current state and the end goal allows an enterprise to focus its resources to achieve the future state, with a well-communicated roadmap.

MxD's technology strategy embodies this philosophy by evaluating the current state of digital adoption within the U.S. manufacturing base. This is done by surveying members and stakeholders to determine the manufacturing capabilities they look to achieve via digital manufacturing. Our strategy then focuses on developing projects, collaborations, and best practices to bridge the gap between the current and future state.

1 U.S. Census Bureau, "2020 County Business Patterns," 2020, **https://www2.census.gov/programs-surveys/susb/tables/2020/us_state_6digitnaics_2020.xlsx**, accessed October 14, 2024.

2 Manufacturers Alliance, *Digitalization Gains: Manufacturers Forge Ahead with Digital Transformation*, 2024, **https://www.manufacturersalliance.org/research-insights/digitalizationreport**, accessed October 14, 2024.

The critical role of data has been the underlying theme across these surveys and discussions. Manufacturers' ability to analyze data more quickly, efficiently, and securely brings about the ROI they seek. Digital adoption is based on utilizing technological capabilities that allow continuous improvement, as measured by data. Data flow is the crucial link that binds people, processes, and technology throughout the supply chain. Understanding data flow is essential for successful digital adoption.

Figure 1: Illustration of the Product Lifecycle and How the Flow of Data Represents a Complex Interconnected Web Among All Aspects

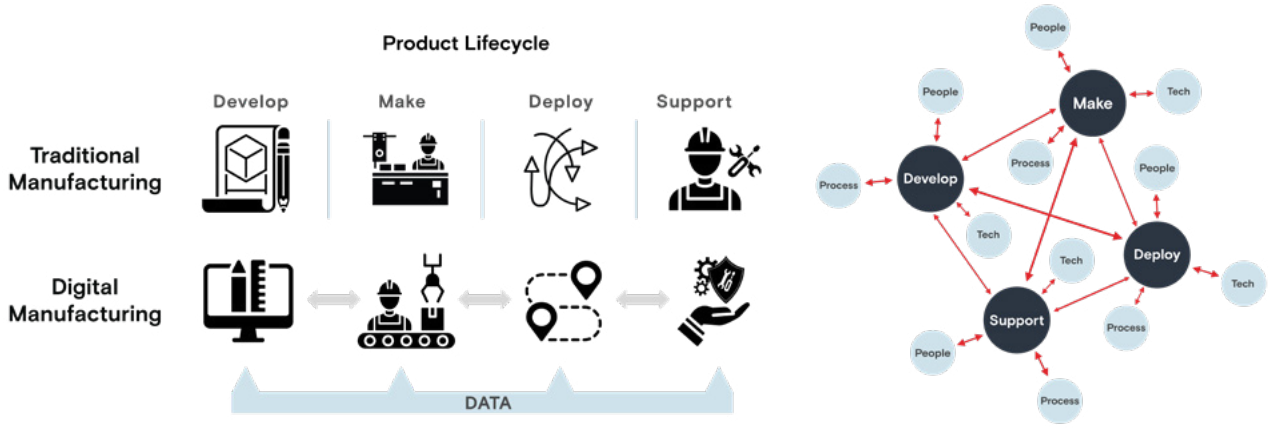


Figure 1 illustrates the complexity of data flow across the product lifecycle. In a traditional operation with minimal to no digitalization, moving data across the product lifecycle is labor intensive and highly dependent on individuals moving across silos. The promise of Industry 4.0 was to link data across the silos and ensure connectivity and visibility across the product lifecycle. The illustration on the right of Figure 1 shows the complexity of data movement. A holistic strategy for data movement encompassing the entire supply chain is necessary; otherwise, successful pilots result in dispersed islands of excellence.

SMMs tend to struggle the most with data as there is no single clear path for digital adoption. Moreover, they lack the resources, workforce, and capital to implement the technologies necessary to derive value from Industry 4.0. Solution providers with newly developed technologies can help and are part of the answer; however, they generally focus on niche solutions. MxD seeks to remedy these challenges by prioritizing efforts that bring about relevant playbooks, novel and secure low-cost solutions, and accessible upskilling resources that SMMs can readily leverage to advance their digital adoption efficiently.

DATA LIFECYCLE

Continuous improvement involves using data to answer questions and make decisions more effectively. Based on a decade of feedback from manufacturers of all sizes regarding their pain points in digital adoption and implementation, MxD recognizes the need for a common language about data. Framing the discussion around where a manufacturer is challenged within the data lifecycle enables a clear pathway to prescribe change and, ultimately, to achieve impact.

We define the data lifecycle as the stages through which a manufacturer's data goes to unlock a critical capability, as defined by the manufacturer. Table 1 describes the stages in detail. Note that to achieve a capability (e.g., machine health monitoring), it is essential to know what technologies are leveraged at each stage so that they can interact effectively to transmit data from one stage to the next. Such an approach has many benefits, including enhanced decision-making, operational efficiency, cost optimization, compliance, security, and integration of advanced technologies. The goal is to curate high-fidelity data from genesis to analysis by establishing clear data governance policies, standardizing data management processes, investing in training and culture, utilizing advanced technologies, and developing a centralized and secure data repository. Access to high-quality, high-fidelity data will, in turn, provide insight for overcoming manufacturing challenges and generate impactful business solutions.

Table 1: The Data Lifecycle with Examples of Early and Advanced Capabilities at Each Stage

DATA GOVERNANCE STAGES		Early	Advanced
	GATHER: What are the sources of data?	Random, as needed Limited networking	Defined locality, frequency, and fidelity Hybrid wired / wireless networking
	CONTEXTUALIZE: How do you give data meaning?	Solution dependent	Defined metadata, enterprise > industry
	AGGREGATE: How do you store data?	Local, point storage	Structured, enterprise and cloud
	VALIDATE: How do you verify fidelity and sensitivity of the data?	Open loop, no validation	Closed-loop validation with self-learning
	SECURE: How safe is the data?	Minimal, IT focus	Industry certified, integrated approach
	COMMUNICATE: Who is transmitting the data and how?	Ethernet/Dashboards	Enterprise standards > Industry standard
	ANALYZE AND APPLY: What can you do with the data? How can the data be applied?	Go/no-go applications Basic point alerts Limits-based analytics In-house focus	Descriptive AI & predictive AI Diagnostic AI & prescriptive AI Real-time digital twins Supply chain and external visibility

EXECUTION OF THE DATA LIFECYCLE

Over the past decade, MxD has led a portfolio of $415 million in public-private investment supporting 189 research and development (R&D), cybersecurity, and workforce development projects. These projects have spanned the manufacturing lifecycle and across the entire supply chain. Projects focused on improving efficiency, quality, and safety and reducing risk have provided participants with millions of dollars of impact. For example, Project 22-06-01, Proactive Worker Safety for Industry 4.0 Using AI, used artificial intelligence (AI) in computer vision and the Internet of Things (IoT) to reduce worker fatigue, addressing a $136 billion problem for employers. In addition, we developed solutions such as the MxD Sensor Kit as a low-cost first step in understanding the potential return on investment digital adoption brings to SMMs.

As MxD focuses on scaling impact, we will focus on demonstrating the value at the project level and across the entire U.S. industrial base. Table 1 describes the data lifecycle and provides a framework for understanding where technology gaps exist and where manufacturers are struggling in the different stages of data governance. Working closely with our members and partners, we can then identify niches for MxD to pursue funding opportunities with our members to help address these technology gaps.

Figure 2: Illustration of a Strategic Roadmap That is Plotted Against the MxD Data-Driven Framework to Advance a Technical Capability and Realize a Meaningful Business Solution

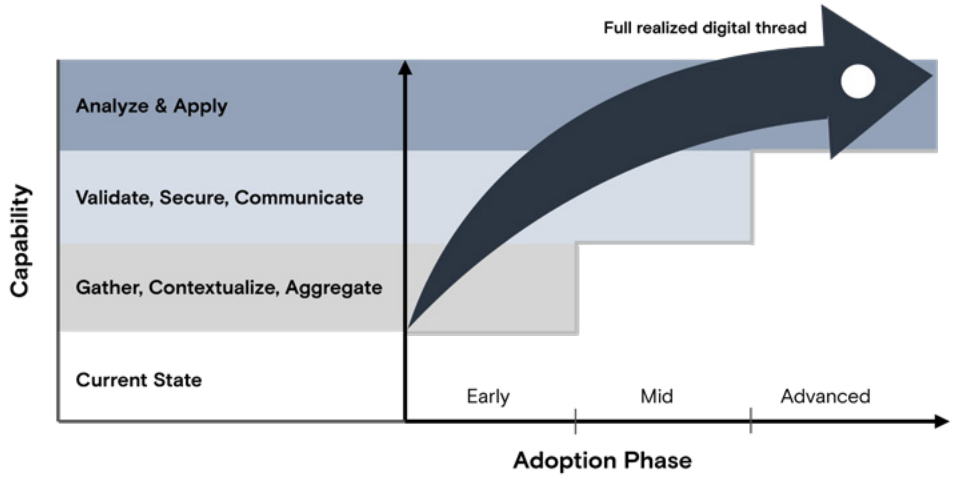
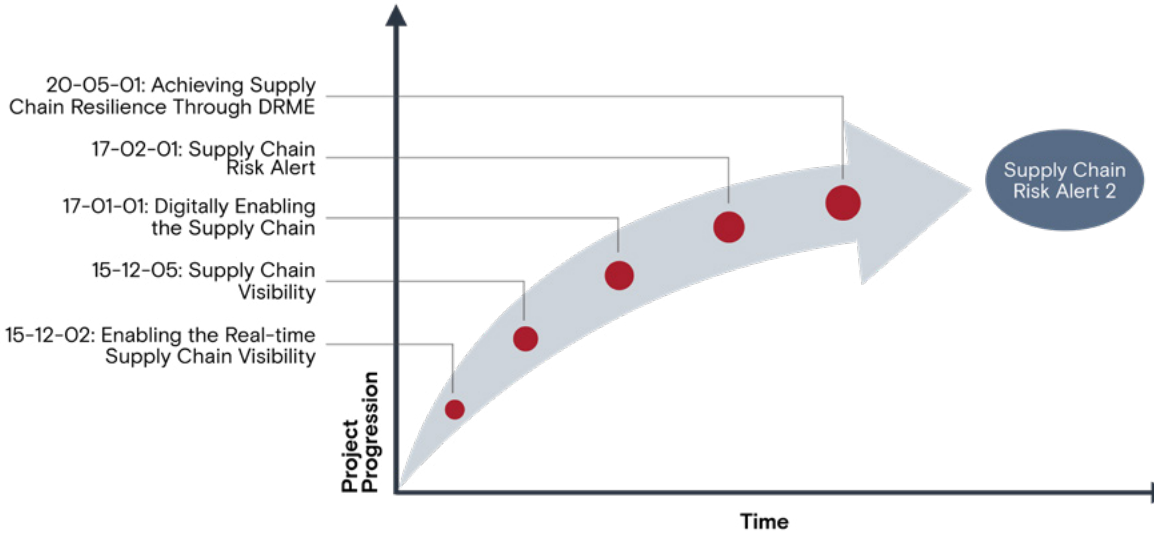


Figure 2 illustrates how data governance involves a progressive process for developing a desired manufacturing capability. Capabilities are realized in steps, whereas the quality of data and analysis improves as a manufacturer's enhancement of a given capability increases. MxD's 10 years of project outcomes serves as the foundation for applied research and technology development for the manufacturing community. Using this foundation as a starting point, our projects seek to advance capabilities and corresponding technologies with our members and broader industrial base to further U.S. manufacturing writ large and achieve a fully realized digital thread.

Advancements in manufacturing capabilities, in turn, must provide value and ROI. This value manifests as a business solution that enables an organization to improve products faster or to reduce product costs. Figure 3 demonstrates how, thanks to our ongoing investments, MxD projects fostered the maturity of capabilities, culminating in the development of a supply chain risk assessment tool with scalable potential.

Figure 3: Progression of Supply Chain Projects Building to the Development of a Supply Chain Risk Assessment Tool



MxD projects center on advancing technology innovation and adoption. We do this by conducting research to understand market needs, raising awareness, and collaborating with our members to develop solutions and implement initiatives. MxD project concepts are weighed against a variety of considerations including industry demand, scope within the data lifecycle framework, and fiscal feasibility before being integrated into future roadmaps. Oftentimes, the focus of MxD's projects underscores the importance of offering peer experiences via demonstrations and implementations and of providing a platform for members to expand their knowledge of technology to bridge existing gaps. Recently, MxD broadened its focus to include the development of playbooks and how-to guides during project implementations. These guides facilitate technology adoption, provide the foundation most SMMs require to begin or continue their digital journey, and offer larger manufacturers a path toward scaling capabilities across their enterprise and beyond.

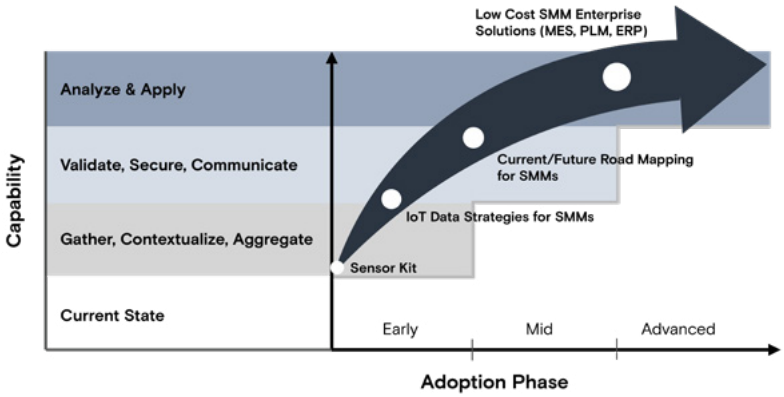
In parallel, MxD Learn emphasizes cultivating a workforce proficient in the technologies and data skillsets that manufacturers need for future operational demands. As baby boomers retire and younger generations pursue careers outside of manufacturing, Deloitte and The Manufacturing Institute recently estimated that between 2024 and 2033, 1.9 million manufacturing jobs could go unfilled if the skills gap remains unsolved.[3] The report also found that manufacturers prioritize developing leadership, digital, and soft skills. These skills can augment mental and physical human capabilities to optimize production, make jobs more accessible, and provide autonomy by giving operators new channels to report production issues. This can enable efficient triage and rapid problem resolution.

Ensuring manufacturers are secure during digital adoption and beyond is paramount. Per IBM's X-Force Threat Intelligence Index 2024, manufacturing was the most attacked sector for the third year in a row.[4] Cybersecurity is no longer an afterthought but must be integrated into the digital adoption strategy and change management of the enterprise's entire operations, from the technology implemented to workforce training and, ultimately, to operations management.

3 John Coykendall et al., "Taking Charge: Manufacturers Support Growth with Active Workforce Strategies," Deloitte Insights, April 3, 2024, **https://www2.deloitte.com/us/en/insights/industry/manufacturing/supporting-us-manufacturing-growth-amid-workforce-challenges.html.**

4 IBM, "IBM's X-Force Threat Intelligence Index 2024," **https://www.ibm.com/downloads/documents/us-en/107a02e952c8fe80**, accessed February 16, 2025.

Figure 4: Example of Project Progression to Advance Digital Adoption Initiatives



MxD's Strategic Investment Plan, with data as the foundation, now incorporates a long-term vision of accumulating project outcomes to bring technology to maturity and to address acute challenges, including cybersecurity and a skilled workforce, as directed by our membership. The Technology Project Portfolio section reflects this change in strategy by demonstrating how projects are advancing a capability within the data lifecycle and how project outcomes build AI readiness and scalability. Figure 4 highlights an example of a capability roadmap where MxD projects are aligned to help manufacturers to adopt digital manufacturing successfully. The MxD Sensor Kit project has developed a successful tool for manufacturers to begin their digital adoption journey by enabling them to gather digital data from legacy systems. As manufacturers, especially SMMs, see the value of IoT in their operations with the MxD Sensor Kit and understand how it can be incorporated, they can then create a digital adoption strategy that best suits their needs. Likewise, MxD projects on our Digital Adoption Roadmap are scoped to develop resources and project outcomes for manufacturers at each subsequent stage of their adoption.

MxD's technology strategy also demonstrates that maturing a technology requires projects to focus on building capabilities that crosscut the conventional MxD categories of Design, Future Factory, and Supply Chain. As such, we've developed a set of capability advancement roadmaps based on the data lifecycle framework to illustrate where MxD projects build capabilities in the following digital manufacturing topics:

- **Maturity Assessment:** Defining a manufacturer's current capabilities to allow for effective strategic digital planning.
- **Data Standards, Architecture, and Interoperability:** Establishing consensus about the minimum required data and the data format and structure to facilitate compatibility across system software and product lifecycles.
- **Digital Twin:** Creating accurate virtual representations of physical manufacturing operations that allow for analysis of those systems without interfering with production.
- **Supply Chain Visibility:** Integrating data across the supply chain to streamline people and processes.
- **Digital Adoption:** Advancing digital adoption as a value-added proposition yielding ROI.
- **Advanced Data Capability Solutions:** Identifying use cases to improve manufacturing operations to leverage once a mature data lifecycle has been established.

MxD plays an essential role in advancing digitalization for the future of manufacturing in the United States, providing value to both government and industry, as discussed in the following sections.

MxD's Value to Government

MxD aligns with the DoD's mandate that a strong defense industrial base (DIB) is a cornerstone of the economic pillar of integrated strategic deterrence. To that end, manufacturing must be considered a lever in the economic element of power for national security. Accelerating the pace of digitalizing U.S. manufacturing serves to bolster and sharpen the effectiveness of the economic leverage that can be applied.

Digital manufacturing can enable OIB modernization that leapfrogs current requirements and into the future. The same digitalization strategy aimed at DIB and non-DIB manufacturers may also be adopted at scale in OIB facilities. Capabilities such as predictive scheduling and maintenance can improve production efficiency while reducing downtime. Digital twins can help with effective asset and logistics planning. The MxD Sensor Kit makes it possible to collect data on traditional manufacturing processes and empower a site with data-enhanced decision-making for the first time.

Decades of evidence show that a resilient and skilled manufacturing workforce is a prerequisite to a secure OIB and DIB. The OIB and DIB, cornerstones of national security and economic stability, each face a significant shortage of workforce trained to utilize basic digital skills and advanced manufacturing technologies such as AI, data analysis, cybersecurity, and extended reality (XR). This skills gap — especially at SMMs — undermines the OIB's and DIB's ability to meet current demands and adopt productivity-enhancing technologies, threatening their effectiveness and resilience. MxD Learn makes digital manufacturing training and careers accessible to hundreds of thousands of learners and workers in support of U.S. economic prosperity and national defense.

National — sometimes global — supply chains are critical for mission success. Large manufacturers can afford to protect themselves against highly skilled adversaries. As a result, adversaries target SMMs, which can undermine the trusted relationships SMMs have with large firms. As the National Center for Cybersecurity in Manufacturing, MxD has spent several years developing cybersecurity offerings and undertaking cybersecurity projects in response to the rising threat to the manufacturing sector.

MxD's Value to Industry

As a neutral voice in digital and cybersecurity for manufacturing, MxD brings value to industry by defining the critical areas required to promote the competitiveness of America's manufacturing base. Being a public-private partnership, we foster collaboration among academia, industry, and government to share best practices and learned outcomes from our joint efforts and projects.

Regardless of the industry, manufacturers strive for more resiliency, particularly in their supply chains. The continued growth of the Industrial Internet of Things (IIoT), machine learning (ML), AI, and robotics for automation has brought the importance of data to the forefront. Manufacturers seek use cases for implementing data-driven workflows with a clear ROI and detailed implementation steps. Data-driven workflows rely on clear and consistently practiced standards when generating and managing data, in other words, data governance. Data governance across the lifecycle from gathering, contextualization, aggregation, validation, and reusability is a fundamental requirement that can significantly affect a manufacturer's competitiveness. Improved competitiveness via effective data governance manifests itself through streamlined operations management and organizational performance, particularly in future factories.

MxD has noted consistent themes around IIoT and AI that have emerged through surveys, one-on-one conversations, and research activities in manufacturing. Manufacturers agree that IIoT technology plays a critical role in predictive maintenance, providing real-time monitoring, data collection, and analysis of machine performance. One challenge is the continued need for manual intervention once data is collected to perform the additional tasks because of a lack of interoperability. In addition, there are not enough open protocol machine controllers to support communication across systems.

Manufacturers are interested in and eager to adopt a proactive approach that enhances operational efficiency and prepares them for potential issues. Their enthusiasm is particularly evident in their interest in an integrated IIoT-based real-time manufacturing execution system (MES) and manufacturing operations management (MOM) software. The lack of off-the-shelf solutions to combine these elements presents a significant challenge while also fueling the industry's momentum to innovate and develop new solutions.

Areas of interest for leveraging AI include automating and improving the accuracy of inventory counting, optimizing stock levels, forecasting future inventory requirements through advanced ML algorithms, and capturing and analyzing institutional knowledge.

To effectively leverage IIoT and AI, the importance of defining and establishing effective data governance cannot be overstated. Manufacturers are urgently prioritizing technologies for cleaning and tagging data as well as tracking designed and as-built features over a product lifecycle. They also want to turn raw data into meaningful insights by aggregating and summarizing important features. A structured approach to data management is necessary to enable future analysis of manufacturing processes and machines and to support traceability across internal systems and supply chains. Furthermore, businesses need to appoint data stewards to oversee data quality checks and integrity and establish ownership of data pipelines.

Although manufacturers have made progress in securing data through a mix of on-premises and cloud solutions that meet most security demands, there are disparities in cybersecurity capabilities between original equipment manufacturers (OEMs) and their supply chains. There is also a lack of clearly established guidance on how to incorporate CMMC requirements. As a result, many organizations are considering no longer supporting DoD contracts.

Regarding data analysis and application, many manufacturers are focused on technologies to support statistical process control analysis, anomaly detection, and historical data analysis. These allow for performance comparisons across various metrics, such as machine utilization, machine downtime, and the quality of parts. Such retrospective views enable the identification of trends and patterns to optimize processes. Our 2025-2027 SIP emphasizes technology initiatives and roadmaps to assist manufacturers in using data to enhance their competitiveness.

Overall, MxD brings value to industry by consolidating needs, matching them to technology, demonstrating application, and de-risking adoption.

MXD LEARN AND INDUSTRY INITIATIVES

To ensure the success of digital adoption, it is paramount for manufacturers to have a workforce that understands the importance of the data lifecycle and its implementation in the areas required for their organization to succeed. To complement MxD's technical projects, MxD Learn offers the following programs and resources directly to the industry through its Virtual Training Center (VTC):

- **CAPITAL (22-25):** The Curriculum and Pathways Integrating Technology and Learning (CAPITAL) program prepares current and prospective workers for a future in digital and cybersecurity jobs for manufacturing by establishing five role-based curricula and training programs in data analytics, cybersecurity, and XR.

- **CyMOT (22-14):** The Cybersecurity for Manufacturing Operational Technology (CyMOT) program is a partnership between the University of Maryland Baltimore County and MxD to increase the security of U.S. manufacturers against cybersecurity attacks. It does this by providing role-based training to the next generation of cybersecurity workers in manufacturing.

MXD CYBERSECURITY INDUSTRY INITIATIVES

MxD continues strengthening our capabilities as the National Center for Cybersecurity in Manufacturing to provide much-needed support for the manufacturing industry to become cyber secure in the ever-evolving threat landscape. We are targeting two complex challenges common to U.S. manufacturers: 1) adopting technology to modernize factory operations and 2) ensuring a high standard of cybersecurity across information technology (IT) and operational technology (OT) infrastructure.

To address these challenges, MxD executed DERISC (23-09): The Digital Education, Resilience, and Innovation for Supply Chain project, in collaboration with the Defense Logistics Agency (DLA). MxD provided U.S. manufacturers with a unified and systematic approach to renewing and securing their supply chains by developing and providing them with the tools, protocols, skills, and information they need for a secure digital transformation.

The cybersecurity posture of most SMMs is grossly underdeveloped due to a lack of cyber awareness and insufficient cybersecurity resources. The tools created by MxD through the DERISC project are targeted to address these issues. MxD is continuing to prepare SMMs for the growing landscape of cyber threats as the U.S. manufacturing community continues its digital transformation. The success and impact of the DERISC resources serve as a foundation for MxD to leverage in future cybersecurity projects and programs.

MxD reached thousands of manufacturers through the DERISC program's initiatives, spreading awareness of DoD cybersecurity compliance frameworks and providing resources for manufacturing organizations to improve their cybersecurity posture. The MxD Cyber Marketplace was a resource for manufacturers to self-assess their compliance with CMMC, National Institute of Standards and Technology (NIST) 800-171, and other frameworks. The platform had over 400 user registrations, with 121 assessments completed before shutting down in August of 2024.

MxD helps propagate cybersecurity skills and knowledge by leveraging the MxD Learn VTC, a platform offering curated courses to develop manufacturing workers' digital skills, including cybersecurity. As of early 2025, the platform offers around 20,000 courses.

In addition to delivering cybersecurity resources to manufacturers directly, MxD is partnering with Tier 1 and Tier 2 members to offer their suppliers a turnkey cyber communications program, called the MxD CyberSecure Supplier Program. The program helps large OEMs build more secure and resilient supply chains by raising awareness about cyber compliance, especially for the DIB. Reaching thousands of suppliers a month, the MxD CyberSecure Supplier Program is an example of how MxD pilots a program — in this case with Rolls-Royce — and then scales it, delivering it to three additional members as of 2024.

MxD's Technology Demonstrations

Factory Floor Update

MxD's Factory Floor is a 22,000-square-foot asset with capabilities that include demonstrating technologies, running testbeds, training workforces on new systems and tools, and illustrating the critical need for cybersecurity in manufacturing. The Factory Floor hosts more than 10,000 visitors annually. It is a facility where everyone from a student to a CEO can experience the potential of advanced digital technology. Visitors already familiar with modern factories can further explore how the cyber-physical world of digital manufacturing can transform their facilities to offer the adaptability of high-mix, low-volume capabilities with the scalability of mass production. The Factory Floor also shows visitors how to think strategically about manufacturing data from a holistic view and how to leverage digital solutions to solve fundamental manufacturing challenges.

The Factory Floor's testbeds were designed and have been used since their inception to demonstrate digital manufacturing use cases and solutions to visitors. In 2017, the MxD digitized manual assembly line opened, and in 2019, the discrete manufacturing testbed, the Cybersecurity Wall, and the cybersecurity process testbed were introduced. These testbeds evolve as they are updated over time.

The discrete manufacturing testbed is an example of such evolution. It produces MxD-branded tokens while showing visitors practical examples of what digital manufacturing and a comprehensive data strategy enables via digital workflows, digital twins, and analytics. These capabilities demonstrate the impact of data collection and closed-loop analytics by gathering and aggregating data from various points in the manufacturing process and illustrating methodologies to analyze the data. The discrete manufacturing testbed's latest iteration (described in the 2025 MxD Demonstration Space Updates section below) advances the level of data and process analysis with the implementation of two digital twins. A digital twin is a virtual replica of a physical asset, process, or system that enables simulation and detailed analysis. The first digital twin mirrors raw material status whereas the second mirrors the production process, enabling in situ changes in production without disrupting or stopping the physical production process. Ultimately, the testbeds allow members to experiment with new ideas and test proofs-of-concept in a controlled environment before deploying them in a production facility.

MxD's Digital Twin Testbed for Process Manufacturing is another example of a demonstration that teaches manufacturers how to implement advanced technologies in their own operations. To create the testbed, MxD partnered with Dow and Siemens. Since the project's 2021 launch, it has allowed companies to see how to design, monitor, and maintain their products more effectively and efficiently, and even remotely, using data and digital tools. Key to the testbed is a digital twin, which the testbed integrates with other cutting-edge technologies such as IoT, augmented reality (AR), and mobile worker tools. The testbed demonstrates how these technologies can be combined with hardware to enhance process manufacturing (where many methods and workflows have remained relatively untouched for decades). Through hands-on demonstrations, manufacturers see how digital twins can improve efficiency, reduce downtime, and enable remote operations.

The manufacturing sector is currently the No. 1 target for cybersecurity attacks. In a world of increasing interconnectivity, hackers have the potential to use one network to get into the other, whether that be IT-to-OT or, more likely, OT-to-IT. This marks an increased risk to a manufacturer's production and data. MxD's Cybersecurity Wall demonstrates how programmable logic controllers (PLCs) found in manufacturing settings can be hacked and the steps that manufacturers can take to mitigate these risks. MxD's Cybersecurity Process

Platform demonstrates cybersecurity in process manufacturing and how manufacturers can detect, respond to, and recover from a cybersecurity attack. Updates to the testbed include Via devices from member Opscura to detect attacks, collect information about any incoming attacks, and safely redirect attacks away from their intended targets. In addition to its use for cybersecurity awareness, the testbed is equipped with more than 28 sensors to monitor the system continuously. Like the discrete testbed data, the data collected on this testbed will be available to members for their use in ML and other AI algorithm development and validation.

Outcomes of select past projects continue to be demonstrated, with a focus on wireless connectivity. 5G continues to be a key enabler for the adoption of digital technology across the U.S. manufacturing base. However, 5G has many different configurations that, when combined with various industries and company sizes, put the rapid adoption of 5G at risk. This is largely due to a lack of understanding about the technology, its application, and how to match the optimal 5G architecture to a specific manufacturer's needs.

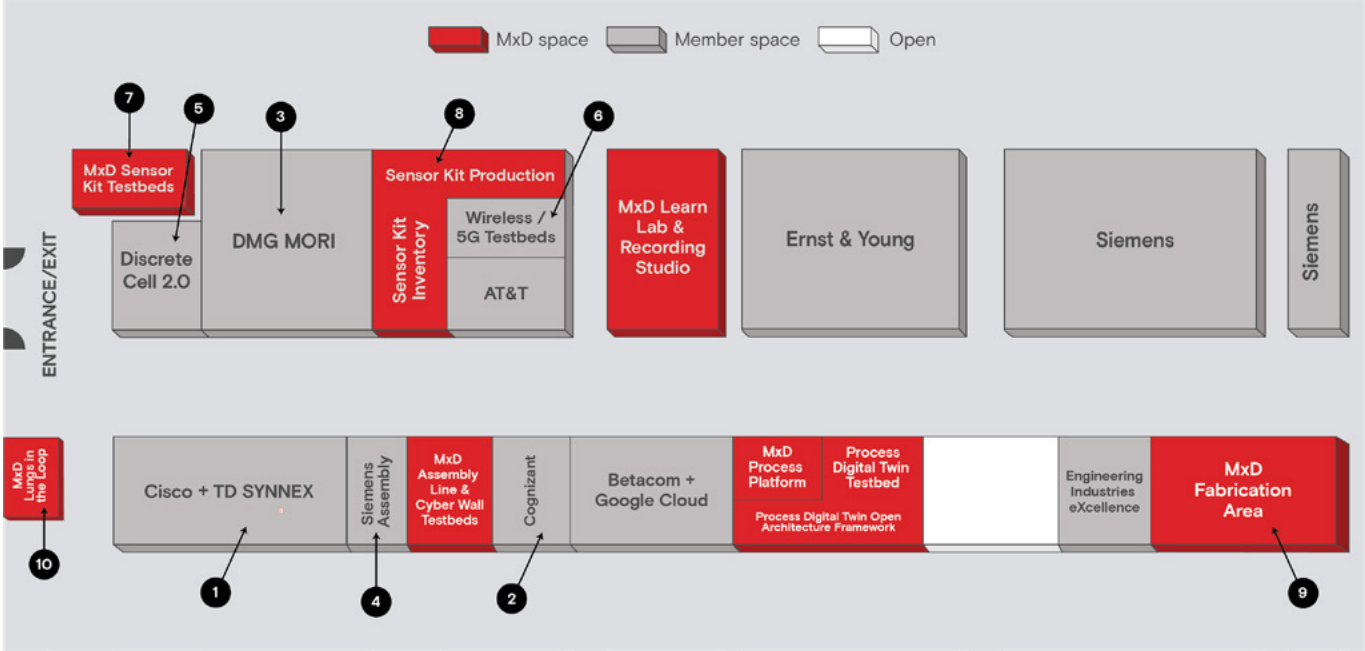
MxD has expanded its 5G capability so that it can demonstrate solutions that are available to meet the varying needs of the broader manufacturing and DoD communities. There are two 5G systems on the factory floor. They are an mmWave non-standalone 5G system and a mid-band private 5G system. MxD member AT&T provides the mmWave 5G system, which is the highest performance system available today, with high throughput and low latency. This is the type of system needed by large, demanding manufacturers with advanced digital requirements. The second is a mid-band private 5G system based on the Citizens Broadband Radio Service (CBRS). The system is maintained by MxD member Betacom. This type of system uses unlicensed mid-band spectrum in exchange for lower performance. The cost of the system, both in terms of initial investment and ongoing maintenance, is significantly lower than that of a high-band system. This type of system is potentially a better fit for the SMMs that make up over 90% of the manufacturing base.

FACTORY FLOOR PLANS FOR 2025

The Factory Floor is a dynamic and evolving space. MxD's team of engineers regularly expand existing testbeds, create new demonstrations, and provide support as members bring exciting new technology showcases to the floor. Some of MxD's members, including Siemens and EY, have built innovation centers inside MxD where they host events and clients on a weekly basis to solve problems and dig deep into existing solutions. Other members have followed suit, with AT&T, Betacom, Cisco, Cognizant, DMG MORI, Google Cloud, and TD SYNNEX all providing cutting-edge technologies on the Factory Floor and hosting manufacturing clients at MxD to solve the biggest manufacturing problems. Visitors are encouraged to return often to experience new solutions and delve deeper into existing solutions to better understand how digital manufacturing will help U.S. manufacturing continue to succeed.

The Factory Floor offers both in-person tours and a virtual tour, which is available at **https://virtualtour.mxdusa.org/bk/public/**

Figure 5: MxD Factory Floor Schematic



NEW MEMBER DEMONSTRATIONS ON THE FACTORY FLOOR

Figure 6 illustrates the Factory Floor layout as of 2025, with the following new MxD members demonstrating their capabilities in their respective spaces.

1. Cisco and TD SYNNEX, in collaboration with Intel, are using this space to test and demonstrate new technology, train workers on these new systems and tools, and demonstrate the need for cybersecurity in manufacturing. These demonstrations include market-ready AI and IoT solutions to secure, communicate, and analyze data.
2. Cognizant launched its Manufacturing Innovation Center in 2024 to demonstrate how manufacturers can improve production operations at scale. Cognizant is uniquely positioned to help clients unlock value through the confluence of technology, data, computing, and AI. This aligns with how to secure and communicate data as well how to analyze data to gain insight.
3. DMG MORI's new space houses an installation highlighting the company's latest technology and demonstrating the capabilities and applications of advanced manufacturing in meeting the demands and conditions experienced by the U.S. military across the globe.
4. Siemens upgraded the Assembly Testbed to represent in detail complex assembly operations for two industries: aerospace and life sciences. In both cases, the assembly process uses best practices, optimized with a digital twin, for both human operations and collaborative human-robotic operations. Visitors learn the value of the digital twin and how it contributes to the manufacturing process plan, as well as how MES drives the execution of the bill of process in different ways to best assist operators. In addition, integration with mobile robots to move parts around the shop floor makes the assembly operations part of a much larger digital-thread-based execution. New and legacy technologies are constantly added to the testbed, creating a live evolving environment.

2025 MXD DEMONSTRATION SPACE UPDATES

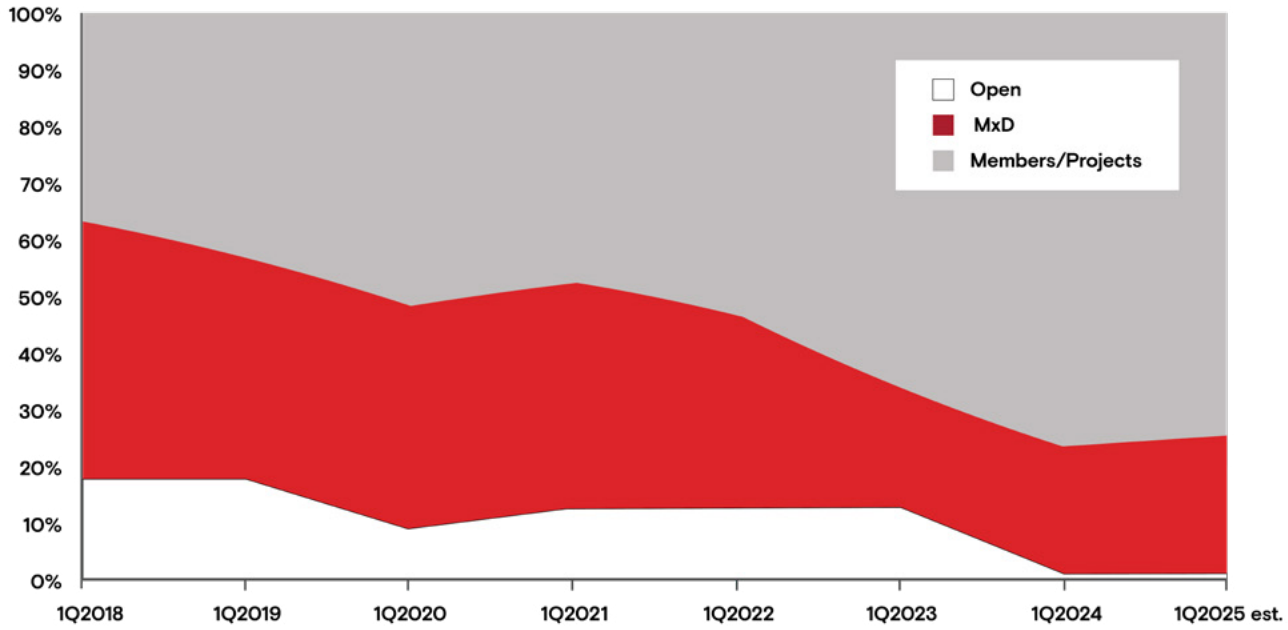
5. Discrete Cell 2.0 is the space for 20-18-02 Capacity and Mobilization: Digital Twin Virtual Commissioning Scenarios, which replicates the manufacture of engraved aluminum tokens with two digital twins. Siemens and Engineering Industries eXcellence will lead this effort. The first is a descriptive digital twin of the entire testbed that enables the user to monitor the status of raw and work-in-progress materials to prevent process shutdowns due to material shortages. The second digital twin is a virtual commissioning digital twin of a cobot[9] that transfers material throughout the cell. This enables the user to make programming changes to a cobot control system to optimize the throughput of the cobot without interrupting production. The testbed was made in the MxD Factory Floor for demonstration, education, and use case testing and was brought online February 28, 2025. This testbed provides an example of how the MxD data-driven approach can be used to govern data through its lifecycle and then leveraged for production optimization.
6. The Construction Engineering Research Laboratory (CERL) 21-18 program seeks to establish a methodology to investigate and test the various types of 5G cellular architecture, 5G cybersecurity, and IOT applications of 5G wireless technology to determine the appropriate configuration for use in manufacturing facilities. Items such as wireless sensors, control systems, and related equipment will be tested within the facility over various conditions. Test results, lessons learned, and best practices will be made available for publication. The 5G system will also serve as an ongoing testbed for industry and DoD for additional use cases in the future.
7. The MxD Sensor Kit Testbed space is where visitors can see how the MxD Sensor Kit works. We designed and developed the MXD Sensor Kit to address an industry need for low-cost data acquisition hardware that can be used to link legacy equipment to modern systems. The solution can be used for a variety of sensors, including proximity, level, spill, amp draw, and flow rate, to list a few. The space has two benches. The first bench demonstrates how the MxD Sensor Kit can be used to shut down a simple drill press when a predetermined amp draw limit is passed. The second bench, referred to as OEE Lite, has one MxD Sensor Kit used to calculate production rates and equipment status of equipment. In addition, data from the bench is transmitted via Wi-Fi to a separate status dashboard. This process of how to gather and aggregate data, how to communicate data, and how to analyze and use data aligns with the data-driven approach MxD is taking toward digital adoption.
8. The MxD Sensor Kit production area and inventory storage space are used by MxD to build the sensor kits and associated sensors.
9. To create space for new members, the MxD fabrication area was reduced and moved to the back corner of the Factory Floor.
10. MxD and Siemens' Rapid and Secure Deployment of Medical Devices and Instrumentation System, also known as Lungs in the Loop, combines a physical testbed and a simulation model. IoT sensor integration and digital twin technology deliver real-time insights into how a single ventilator can be safely used by two patients.

9 Cobot is a term used to describe a "collaborative robot" which is designed to work and interact with people safely.

FACTORY FLOOR USAGE IN 2025

Figure 7 illustrates MxD Factory Floor space usage trends. Note that member space usage has trended upward over time while MxD and open space have gradually reduced. Full utilization of the Factory Floor's space will be reached in 2025.

Figure 6: Factory Floor Usage Distribution Between MxD and Its Stakeholders



MxD Sensor Kit

SMMs encounter a number of challenges when implementing digital manufacturing. One of the most significant is the limitations posed by legacy machinery, which require the installation of sensors and connectivity features for effective data capture. Upgrading or replacing machinery can be expensive and logistically complex. Financial constraints further exacerbate this issue, since many SMMs operate on tight margins that limit their ability to allocate funds for digital transformation initiatives. This outdated equipment creates a substantial hurdle in integrating new digital technologies.

A lack of expertise within the workforce can also impede progress because employees may not have the necessary skills to implement and manage new technologies. These skills gaps often manifest in resistance to change, with employers and employees alike slow to invest in more training to enable the adoption of new processes. Moreover, organizational culture plays a critical role in embracing new technologies, with some employees perceiving digital transformation as a threat to their jobs, which can create further resistance.

Integration challenges also pose a significant obstacle, as many SMMs struggle to ensure that new digital systems can effectively communicate with existing legacy systems, resulting in data silos and inefficiencies. Ultimately, SMMs often do not perceive a timely ROI from digital transformation initiatives given the often expensive initial capital investment and change management required.

Despite these barriers, focusing on data capture can serve as a promising first step toward digital transformation for SMMs. By implementing basic data capture solutions, even legacy equipment can provide valuable insights. Retrofitting machines with simple sensors can enable manufacturers to collect critical operational data, such as production rates, machine performance, and maintenance needs. This initial step helps generate actionable insights and lays the groundwork for more advanced digital initiatives in the future.

Figure 7: The MxD Sensor Kit in Use

As SMMs become more comfortable with data collection and analysis, they can gradually integrate more sophisticated digital technologies, enhancing efficiency, productivity, and competitiveness in the market.

In this spirit, we created the MxD Sensor Kit in 2023. The device was designed to be a simple, no-code solution that interfaces with most commercially available sensors. It provides manufacturers a cost-effective solution to gather data and monitor various processes more closely (even on legacy equipment) in an effort to reduce downtime and failures. Each MxD Sensor Kit has four digital inputs, four analog inputs, four digital outputs, and a stack light driver enabling a range of use cases. In 2023, MxD conducted a pilot program installing 11 kits at 10 different manufacturing sites. The applications were as varied as monitoring pump health and monitoring fan vibration. In 2024, the program was expanded with the goal to reach 100 manufacturers via a channel partnership program to increase distribution and pave a path to scale toward the goal of enabling 10,000 manufacturers to go digital by 2028.

After an SMM makes its first stride into digital solutions with the MxD Sensor Kit and realizes the benefits of digital adoption, the next step is to develop a roadmap for larger-scale implementation. This involves choosing the appropriate MES, enterprise resource planning (ERP) solutions, and other data analytics tools for their needs. MxD helps guide SMMs in this process by providing playbooks and project use cases.

MxD Learn Virtual Training Center (VTC)

The MxD VTC is an online platform (available at **https://vtc.mxdusa.org**) for empowering the workforce with the skills needed to strengthen U.S. manufacturing competitiveness. The VTC has a robust library of around 20,000 courses that improve workforce competencies across manufacturing business functions. It includes unique MxD-developed learning content that focuses on the future of work in manufacturing, such as courses on data analytics, cybersecurity, and extended reality.

The VTC fills a gap experienced by SMMs nationwide: the lack of resources to purchase learning management systems widely adopted by large companies. Learning management systems enable a culture of continuous improvement, which is a prerequisite to successful digital transformation. When robust learning resources are available to all employees across business functions — from sales to human resources to production — the entire business's digital capabilities are enhanced.

MxD complements the VTC course library with role-based training programs focused on preparing manufacturers for the future of work. These future-looking training programs include:

- Data Annotator
- Manufacturing Analytics Associate
- Cybersecurity Analyst for SMM
- Supply Chain Cybersecurity Compliance Specialist
- Pre-Metaverse Integration Technologist
- Manufacturing Cybersecurity AI/ML Engineer
- Advanced Cybersecurity Analyst

The asynchronous role-based training programs listed above were developed through the MxD Learn CAPITAL and CyMOT programs.

The VTC enables MxD Learn to scale programs beyond their initial audience and grant-funded performance periods to new regions and learners. It provides valuable insights to the MxD Learn team as it develops new programs, including robust data on learner registrations, enrollments, course progress, and completions.

The VTC unlocks several revenue-generation opportunities, including:

- Selling VTC microsites. A microsite is a custom-branded version of the VTC for organizations interested in hosting training courses on a learning management system that costs far less than other training programs or learning management systems.
- Hosting training programs from channel partners looking to extend their reach within the manufacturing sector, with MxD taking a small portion of channel partners' proceeds.
- Licensing VTC courses developed by MxD to other training partners and libraries.
- Selling access to individual courses.

The VTC has immense potential as a platform for all future MxD courses and resources across business verticals. This effort represents the latest strides in attaining the goal of upskilling 1 million manufacturing workers in the United States.

Technology Project Portfolio

DESIGN

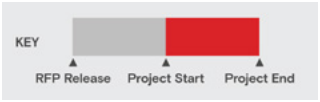


Figure 8: Design Project Timelines

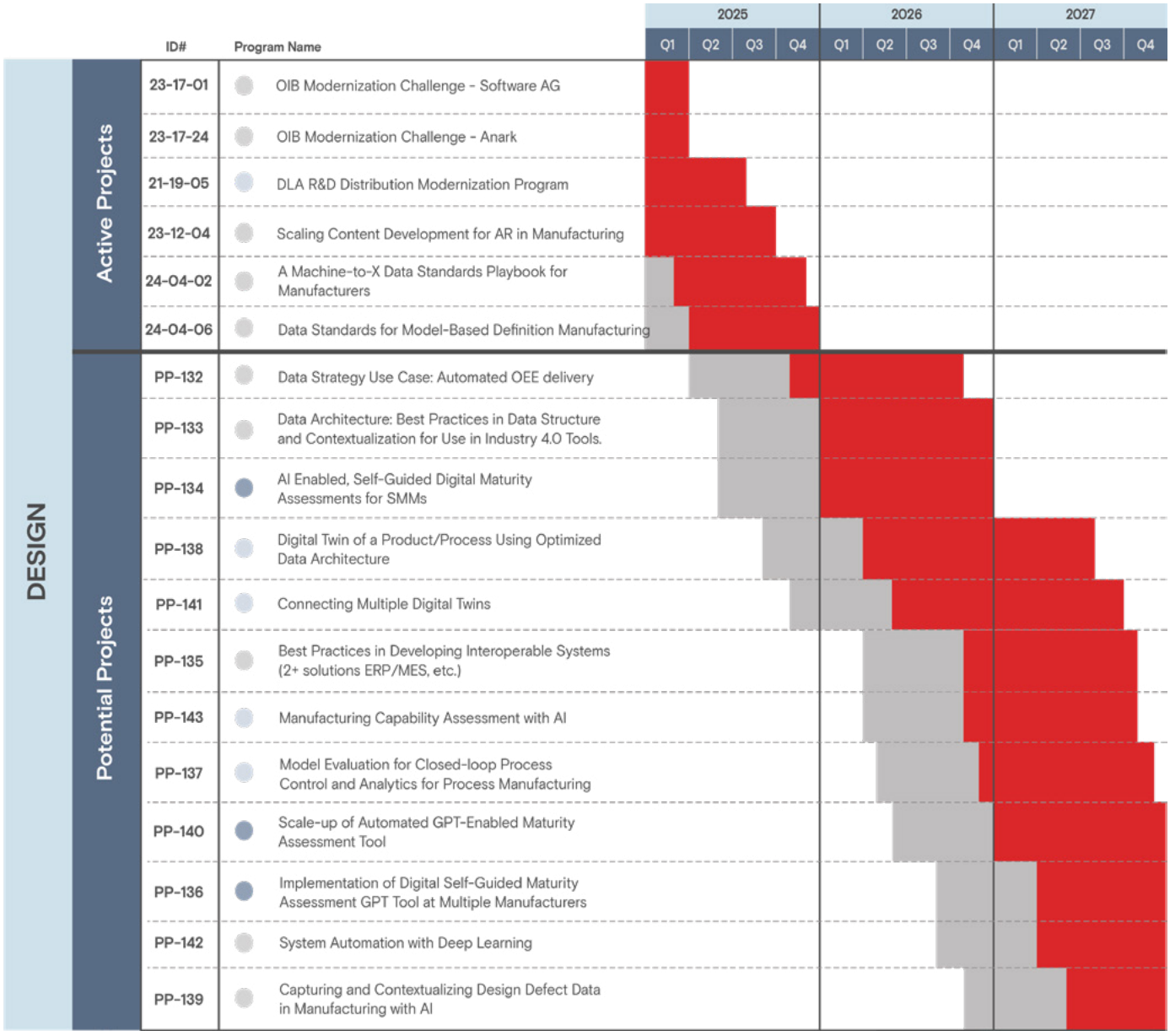
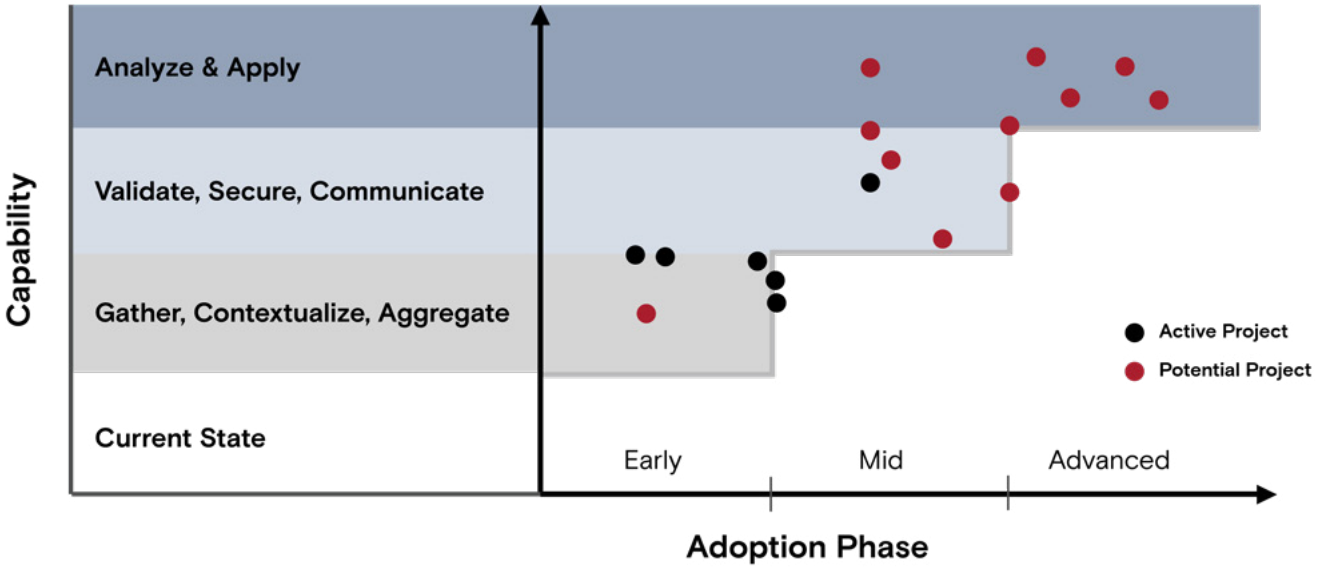


Figure 9: Design Project Distribution with Respect to the Data Capability Framework



ACTIVE DESIGN PROJECTS

21-19-05 DLA R&D Distribution Modernization Program

Project Team: MxD, DLA R&D Strategic Distribution and Disposition

This project supports the DLA R&D Strategic Distribution and Disposition group efforts in its Distribution Modernization Program. It provides subject matter experts' advice and guidance in research, development, testing, and evaluation (RDT&E) activities for Industry 4.0 technologies identified as potential operational transformers at their distribution centers. With expertise in evaluating and implementing existing and emerging commercial Industry 4.0 technologies in the manufacturing industry, MxD is uniquely positioned to share lessons learned in the ever-evolving landscape.

23-12-04 Scaling Content Development for Augmented Reality (AR) in Manufacturing

Project Team: Northrop Grumman, ScopeAR, Ohio State University

Manufacturers would like to use AR because of the proven benefits of visual aids during standard operating procedures (i.e., maintenance) but run into roadblocks when attempting to scale AR throughout the facility or company. This is partly due to the significant consumption of labor and resources related to taking available data (i.e., procedures, CAD, MES, etc.) and using an authoring application to generate the AR content. This project seeks to develop a framework for integrating enterprise systems with AR content generation. The project aims to pave the way for autonomous content generation of deployment-ready AR content to quickly produce work instructions that focus on the worker's information needs, application flexibility, and support for a wide variety of devices with minimum human intervention.

23-17-01 OIB Modernization Challenge - Software AG

Project Team: MxD, Software AG

The Office of the Secretary of Defense (OSD) ManTech program released a call for projects known as the OIB Modernization Challenge that invited innovative solutions to help digitize OIB sites more efficiently. This is one of two MxD projects selected as a result of the call for projects. The overall objective of the Shop Floor Modernization Program is to implement a common set of processes and tools to modernize legacy manufacturing and maintenance facilities. This is done by improving visibility into machine health and utilization to allow leadership to make more educated decisions regarding plant utilization, the quality of parts, safety, and capacity planning. This data can be leveraged to assist with predictive logistics and supply chain.

23-17-24 OIB Modernization Challenge - Anark

Project Team: MxD, Anark

This is the second project associated with the OIB Modernization Challenge's call for projects. Anark is developing a new solution and demonstration combining commercial off-the-shelf (COTS) software, OIB-specific integrations, and OIB-specific content templates that showcase four major capabilities: publishing automation, printing with critical data markings, real-time digital collaboration, and closed-loop paper-to-digital collaboration.

24-04-02 A Machine-to-X Data Standards Playbook for Manufacturers

Project Team: TBA

The complexity of connecting heterogeneous systems (machine, software, enterprises, etc.) through data formats is a significant barrier to adoption of digitalization by manufacturers. Data standards have been developed to address the heterogeneity of manufacturing systems. However, data standards are numerous due to the siloed nature of organizations that develop these standards. This siloed approach makes it difficult for manufacturers to adopt data standards for their use case to facilitate semantic interoperability and consistency between systems. The Machine-to-X Data Standards Playbook will provide a consolidated one-stop-shop resource for manufacturers to determine the appropriate data standards within the product lifecycle. The playbook aims to alleviate the confusion of data standards and provide generalizable recommendations to the manufacturing community to facilitate the adoption of digitalization.

24-04-06 Data Standards for Model-Based Definition Manufacturing

Project Team: TBA

Model-based enterprise assessments have been characterized as not user-friendly and difficult to follow, leading to many manufacturers abandoning the effort after completing the evaluation. The current assessment does not provide any insights on costs, benefits, and, most importantly, the following steps to advance the organization's maturity. MxD is soliciting proposals from organizations interested in executing and refining the assessment based on feedback from industry partners. The key upgrades will focus on the above challenges (cost, benefits, progression, instructions) but may include other elements. MxD is also soliciting interest from industry manufacturers who are interested in taking the maturity assessment.

Future Factory

KEY
RFP Release | Project Start | Project End

Figure 10: Future Factory Project Timelines

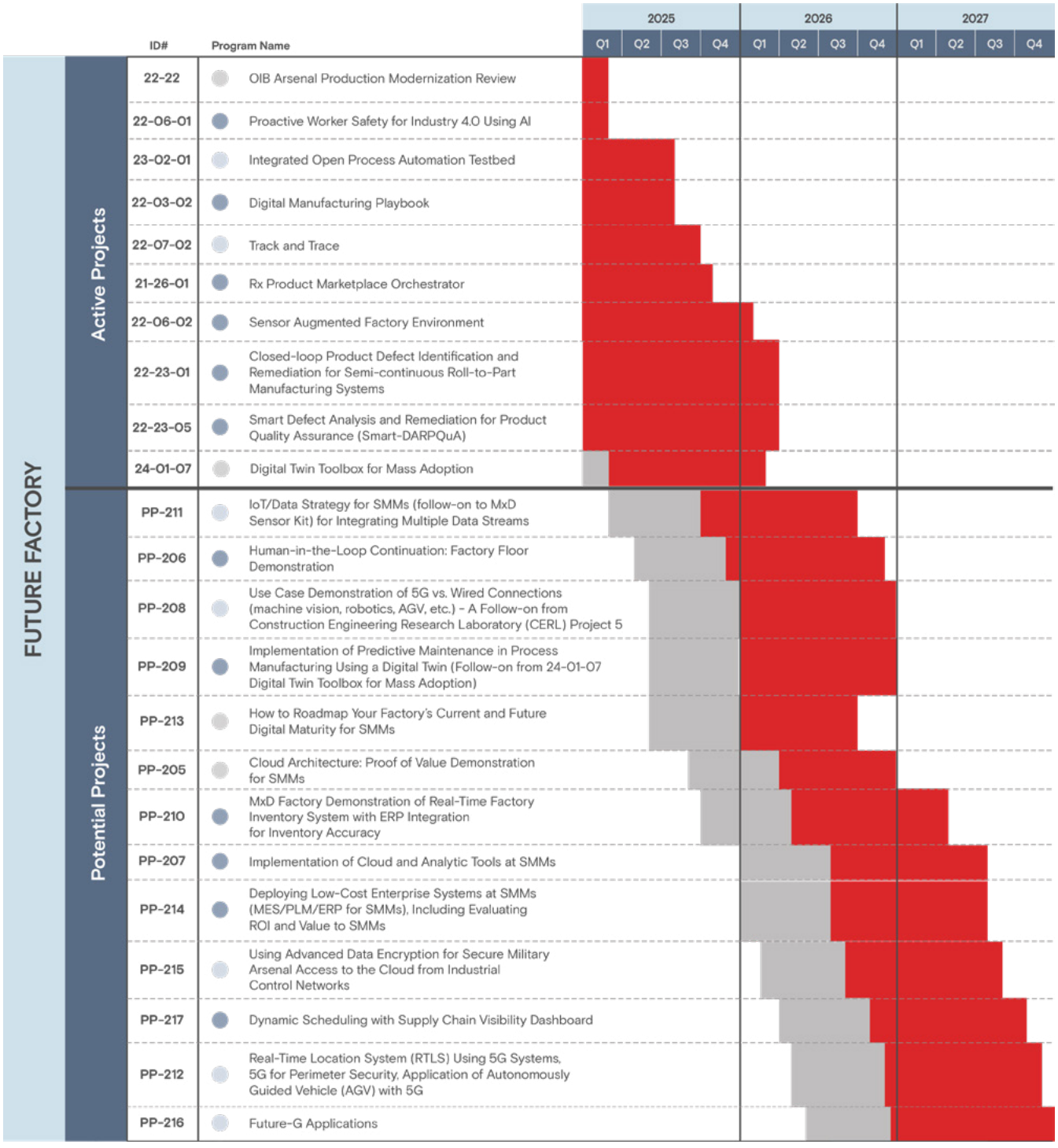
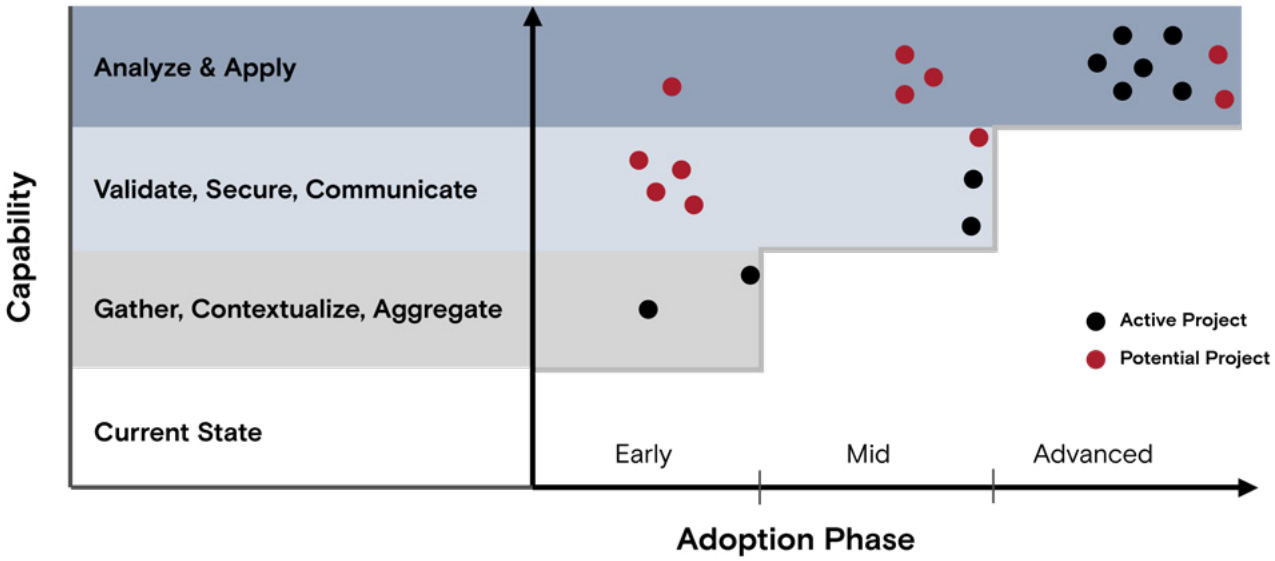


Figure 11: Future Factory Project Distribution with Respect to the Data Capability Framework



ACTIVE FUTURE FACTORY PROJECTS

21-26-01 Rx Product Marketplace Orchestrator

Project Team: MxD, Wayne State University, Oregon State University, University of Dayton

The COVID-19 pandemic exposed a deficiency in U.S. supply chains for rapidly responding to urgent needs. No adequate tools currently exist to support decentralized emergency production and supply. The Rx Product Marketplace Orchestrator will be an online marketplace that will link designers and manufacturers to meet urgent needs during a pandemic and other adverse events that disrupt the supply chain. The platform will include elements to harvest product design and manufacturing information semi-automatically and to perform online matchmaking, offering the ability to fulfill consumer demands from willing and able producers. Orchestration algorithms will maintain constant, manageable demand and ensure capacity utilization, load-balancing between participating producers, and knowledge-sharing for making the demanded goods.

22-03-02 Digital Manufacturing Playbooks

Project Team: Purdue MEP, ConnStep, Catalyst Connection Mursix, BetaShim

The manufacturing industry is in the process of a years-long transition toward Industry 4.0 and is harnessing the benefits of increasingly connected production equipment, business systems, and data. This transition is uneven and varies across industry, region, and company size, but generally, SMMs lag behind their larger counterparts. There are many reasons why SMMs have been slower in adopting advanced manufacturing technologies. Chief among them is the lack of time, personnel resources, or expertise to pursue transformation implementations that may have an uncertain or unclear ROI. There is a significant opportunity for SMMs who quickly adapt to the new landscape to obtain new business or retain current customers. For those who do not digitally transform, there is a growing risk of no longer being able to serve market needs. This project represents a collaboration between MxD and three MEPs, each supporting an SMM through a relatively small-scale, industry-common digital manufacturing implementation. The learnings from these case studies will be combined with their existing expertise to develop a universally applicable, SMM-focused, incremental playbook in short videos that will guide organizations in identifying, comparing, scoping, executing, and evaluating their digital manufacturing implementation outcomes.

22-06-01 Proactive Worker Safety for Industry 4.0 Using AI

Project Team: Be Global Safety (Arvist), University of Buffalo, PPC Flexible Packaging

This project will support the transition of safety processes from a reactive approach to a systems-based and proactive solution while maintaining the employees' privacy. The solution will help present practical training material for safety incidents and provide real-time performance data to the company and the workers. A platform using AI video analytics technology will be developed to give accurate risk assessment of ergonomics of the worker without the need for wearables and understand the "near-misses" or hazardous work conditions, allowing for more proactive solution development in the organization. This platform will work independently of workers, ensuring it does not interfere with the daily operations of the workplace. These technology gaps will be addressed as part of the solution: 1) Employee privacy concerns, 2) Security of the developed solution from a data/cyber perspective, and 3) Meeting data, legal, and regulatory requirements.

22-06-02 Sensor Augmented Factory Environment

Project Team: Boeing, Northwestern

Building on the technical foundation of MxD 19-13, "Human Workflow Digital Twin," this project aims to develop, test, and demonstrate an IoT architectural framework for integrating end-point devices as sensor technologies that assess common worker safety risks in a manufacturing environment. The system, named Sensor Augmented Factory Environment (SAFE), will leverage COTS and open-source capabilities to create a scalable, secure, and sustainable agnostic testbed. It will utilize an edge computing system and standard publish-subscribe messaging to reduce the complexity of point-to-point communications and for internally managed interfacing with the analytics cloud platform. Business rules and workplace safety criteria will be based on published industry standards and best practices. Key performance measures will assess system efficacy and proficiency in providing safety and health management support. The project will also develop a testbed framework for qualifying end-point sensors that integrate with an interoperable IoT architecture. The devices tested in this environment will address risk factors contributing to recurring injuries and incidents across the U.S. industrial base. These include but are not limited to ergonomics, slips/trips/falls, exposure to hazardous energy and materials, working in confined spaces, and noise. The project will also administer surveys to end-users to solicit insights and perceptions regarding safety sensor technology usage and trust.

22-07-02 Track and Trace

Project Team: Connecticut Center for Advanced Research, Search In Real Life (SIRL)

Tracking and tracing assets throughout an organization's supply chain or within its facility has long been a standard practice. Whether an organization knows when to expect components or needs the location of tools or fixtures, tracking and tracing provide value for various groups and job functions. The proliferation of Industry 4.0 and the rapidly advancing state of technologies has led to an abundance of track and trace solutions; however, manufacturers struggle to identify which technologies best suit their needs. This project aims to develop a selection tool for track and trace technologies and solutions. The possibilities and limitations of existing tools and solutions will be measured against the ideal application and produce high-level breakdowns of how the chosen technologies work, costs associated, barriers to adoption, and other pertinent information. Lastly, the data gathered in this project would be used to develop a guidebook that introduces manufacturers to the available solutions and empowers them to make choices that best suit their operations.

22-22 OIB Arsenal Production Modernization Review

Project Team: MxD, America Makes, ARM, LIFT, NextFlex, National Center for Defense Manufacturing and Machining, Office of the Secretary of Defense, Marine Depot Maintenance Command (MDMC), Watervliet Arsenal (WVA)

FY22 National Defense Authorization Act, Section 354 directed a Pilot Program on Digital Optimization of OIB Maintenance and Repair Operations. A team from MIIs formed by the OSD Manufacturing Technology Program will assess two facilities and compile recommendations on solutions matching

the uniqueness of OIB capabilities to modernize operations management. The facilities chosen were the Marine Depot Maintenance Command in Albany, Georgia, and Watervliet Arsenal in Albany, New York. MxD, America Makes, ARM, NextFlex, and LIFT will collaborate to identify and map advanced manufacturing technologies to improve efficiency and effectiveness and sustain next-generation technologies and readiness.

22-23-01 Closed-Loop Product Defect Identification and Remediation for Semi-Continuous Roll-to-Part Manufacturing Systems

Project Team: University of Cincinnati, Kent Displays, Predictronics

Material thickness and uniformity control is a known challenge in most R2R manufacturing processes (e.g., steel casting, liquid-crystal film manufacturing). To meet in-line and post-line quality control needs, many optical inspection devices are utilized to inspect the surface quality (e.g., contaminations, cracks, roughness, etc.) of manufactured parts. However, based on a comprehensive literature survey and discussions with manufacturers, the proposal team found that these optical inspection devices are often siloed in production due to several technical barriers. After understanding these technical barriers, this project aims to develop and demonstrate a closed-loop product defect identification and remediation system based on a roll-to-part (R2P) manufacturing system, where materials from the multi-stage R2R production line are directly cut into finished parts. The proposed system will achieve 1) automated optical inspection with AI-assisted data processing, 2) in-line sensing and monitoring for critical components and subsystems, and 3) semi-automated root-cause identification and intelligent clean room temperature control.

22-23-05 Smart Defect Analysis and Remediation for Product Quality Assurance (Smart-DARPQuA)

Project Team: Siemens, MK Morse, Kent Displays

Although industrial operations have come a long way in the automation era, quality inspection processes remain dependent on human input. Automated defect tracking, trend analysis, and contextualization of defects are required for in-depth understanding beyond today's "scrap vs. no scrap" inspection systems. Therefore, a need exists for an advanced inspection system with automated remediation recommendations to reduce high labor costs, inspector subjectivity, inspector error and fatigue, variation in quality inspection and remediation action, and risk associated with time loss if remediation actions are not taken timely. This project aims to advance in situ quality inspection by developing "Smart Defect Analysis and Remediation for Product Quality Assurance (Smart-DARPQuA)" for two different industry sectors, namely industrial and machine tools manufacturing and electronics device manufacturing.

23-02-01 Integrated Open Process Automation Testbed

Project Team: ADI, Siemens

In 2019, MxD, industry, and the DoD sponsored the development (RFP 19-04: Digital Twins for Process Manufacturing) of a process testbed located in MxD's Factory Floor to meet manufacturers' need to test in a neutral, risk-free environment and enable experimentation with digital technologies for digital twin use cases. The work scope was divided into Part A, Project 19-04-04: Mobile Worker Proof-of-Concept, and Part B, Project 19-04-03: Open Architecture Testbed. This project will integrate the 19-04-04 and 19-04-03 systems to showcase the common strengths of both testbeds, validate the openness of the two testbeds against recent Open Process Automation Forum (OPAF) standards, and create a combined testbed on the leading edge of manufacturing control technology. The final architecture will provide highly available control of the process testbed (actual or simulated). The user can seamlessly interoperate and switch control between various Distributed Control Nodes (DCNs), and toggle between local and cloud-hosted applications.

24-01-07 Digital Twin Toolbox for Mass Adoption

Project Team: University of Alabama in Huntsville, Auburn University, Innovation Machine, MxD Factory Floor

The possibility of digital twins impacting the

manufacturing industry is immense and spans the entire product lifecycle from design to sustainment. However, no two digital twins are exactly alike — to provide value, a given digital twin implementation must match the fidelity and scope of the model to the type of problem being solved. For a manufacturer to decide to invest in a digital twin, they must have an easy-to-use framework and set of tools to be assured that a digital twin is the right tool for the job and will be worth the investment. Building on the Digital Twin Consortium (DTC) framework, this project call will fund the creation of two framework-compliant digital twins — one at a pilot manufacturer and one on MxD's Factory Floor. Through engagement with the DTC, the framework will be stress-tested, and suggestions for enhancement will be made. Finally, additional tools or guidance are being developed to help manufacturers quantify the likely ROI of a digital twin and whether it is an appropriate tool for their problem.

Supply Chain

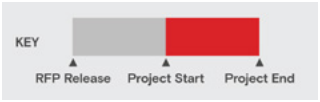
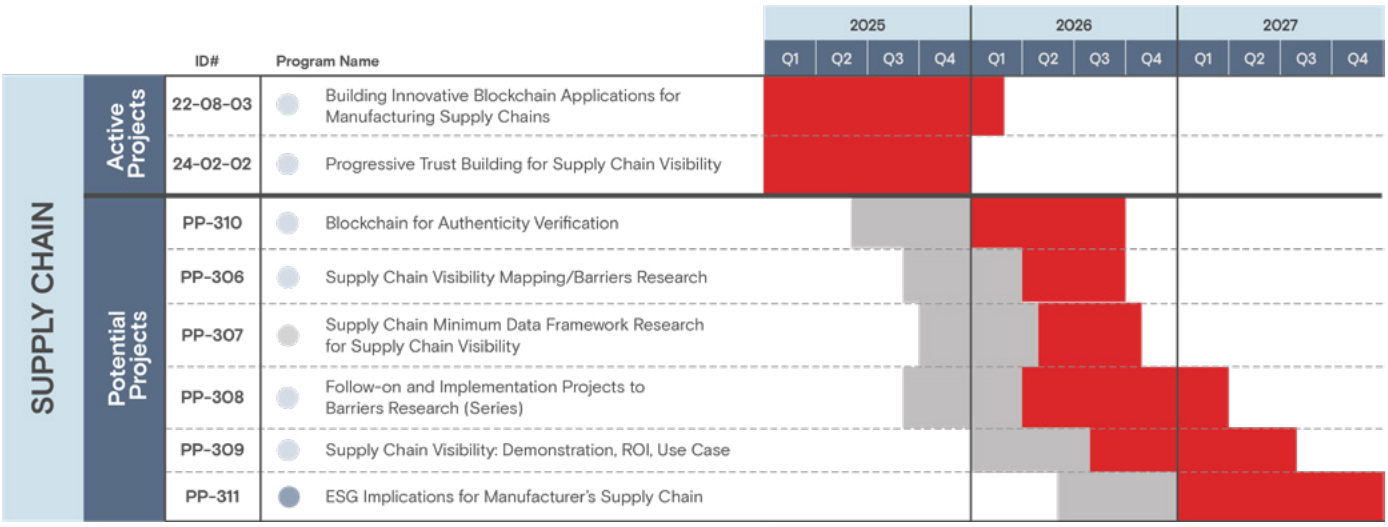


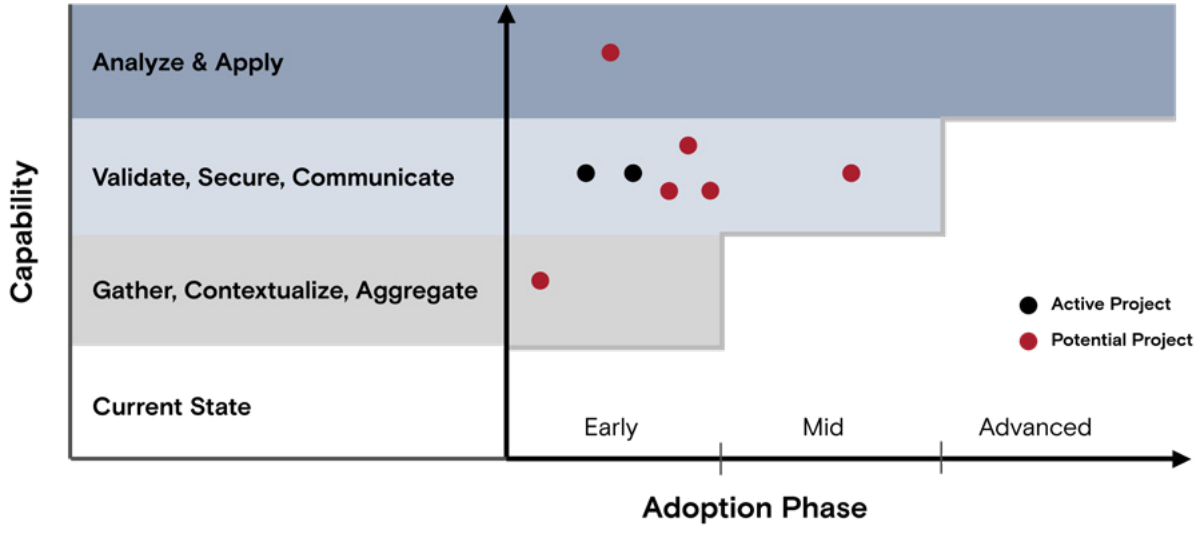
Figure 12: Supply Chain Project Timelines



Data Lifecycle Guide

Analyze & Apply | Validate, Secure, Communicate | Gather, Contextualize, Aggregate

Figure 13: Supply Chain Project Distribution with Respect to the Data Capability Framework



ACTIVE SUPPLY CHAIN PROJECTS

22-08-03 Building Innovative Blockchain Applications for Manufacturing Supply Chains

Project Team: Corsha, Ohio State University

Blockchain technology has many unique attributes that make it attractive for privacy and security. Still, it also suffers from a lack of trustworthy manufacturing case studies and the relative complexity of the architecture. This project will demonstrate an instantiation of a private permissioned blockchain based on IBM's Hyperledger Fabric within an operational manufacturing setting to move proprietary data securely across OT and IT systems. The final deliverable will be an interactive playbook for manufacturers to understand their use case and the blockchain implementation that would bring the most value to their supply chain. The goal is to create a playbook with the ease of use of TurboTax and the ability to be maintained and extended as new use cases and technologies emerge.

24-02-02 Progressive Trust Building for Supply Chain Visibility

Project Team: Supply Chain Risk Management Consortium

Modern manufacturing supply chains are global and distributed, and they include many organizations, from the extraction of raw materials through finished goods. For any large manufacturer or OEM, successfully delivering the end system requires that each link of the chain contributes its portion as expected. However, in practice little visibility into the supply chain exists beyond one tier up or down, which results in unforeseen disruptions and inefficiencies. This project is evaluating the types of data shared across the supply chain, ranking them by level of business risk, and developing a model or tool to enable progressive data sharing for establishing and deepening trusted relationships.

Cybersecurity

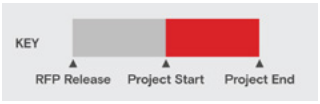


Figure 14: Cybersecurity Project Timelines

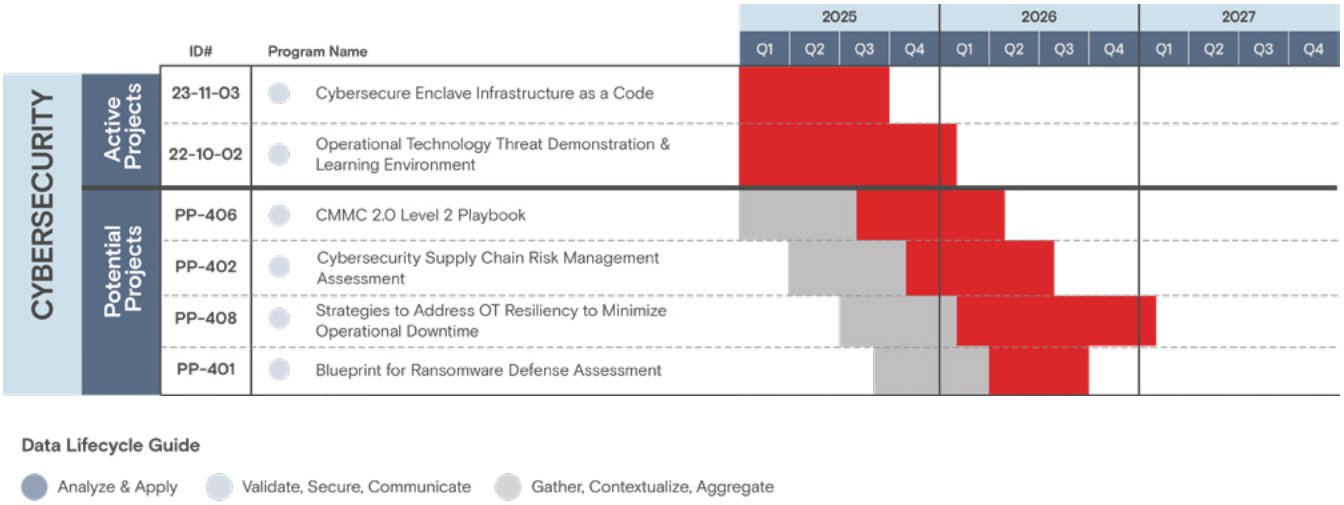
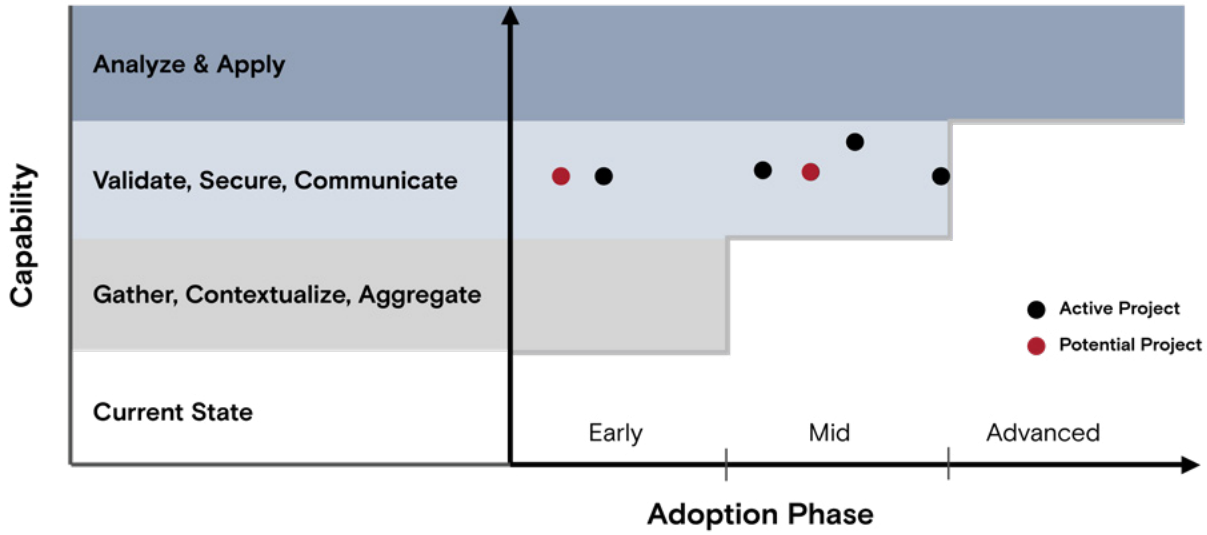


Figure 15: Cybersecurity Project Distribution with Respect to the Data Capability Framework



ACTIVE CYBERSECURITY PROJECTS

22-10-02 Operational Technology Threat Demonstration & Learning Environment

Project Team: MxD

MxD is creating an interactive testbed that will allow industry to use existing tools to better manage their cybersecurity risk and identify gaps in attack profiles that are not sufficiently addressed by existing OT security tools. The testbed environment will represent the tactics and techniques that SMMs can safely and effectively deploy on OT networks. The project includes developing an interactive cybertown to represent a manufacturer's OT system, creating parsers to allow a manufacturer to upload a framework of its OT system to the testbed, and developing an interactive program to allow users to view consequences and outcomes of attacks and preventative measures in real time.

23-11-03 Cybersecure Enclave Infrastructure as a Code

Project Team: NetThunder

SMMs are not typically dedicated entirely to DoD production. These manufacturers do not have the resources to create secure networks for DoD cybersecurity requirements. This results in fewer manufacturers who can support DoD manufacturing priorities with increased operational costs to DIB/OIB suppliers who comply with DoD cybersecurity requirements. It leads to lowered competitiveness of U.S. manufacturing with an inability to realize opportunities for IT/OT-connected enterprises. This project will create a configurable software architecture resource that SMMs can use in their environments. MxD is soliciting proposals addressing the need for a software solution for SMMs to simplify provisioning, deploying, and maintaining a secure network infrastructure for DoD manufacturing production.

Workforce Development

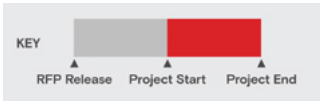


Figure 16: Workforce Project Timelines

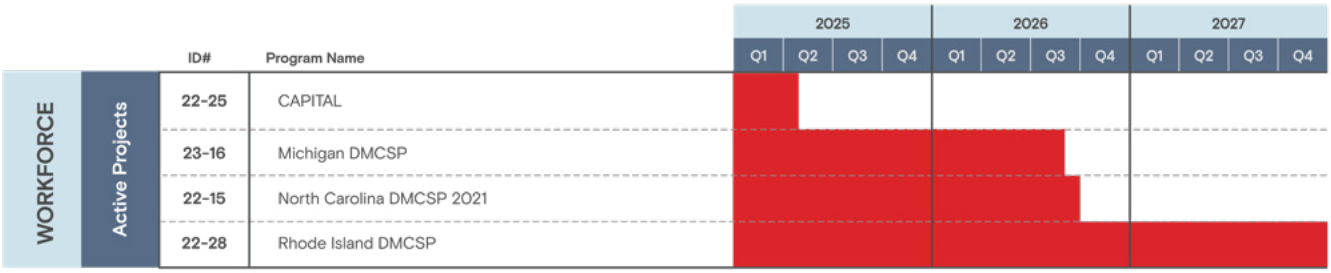
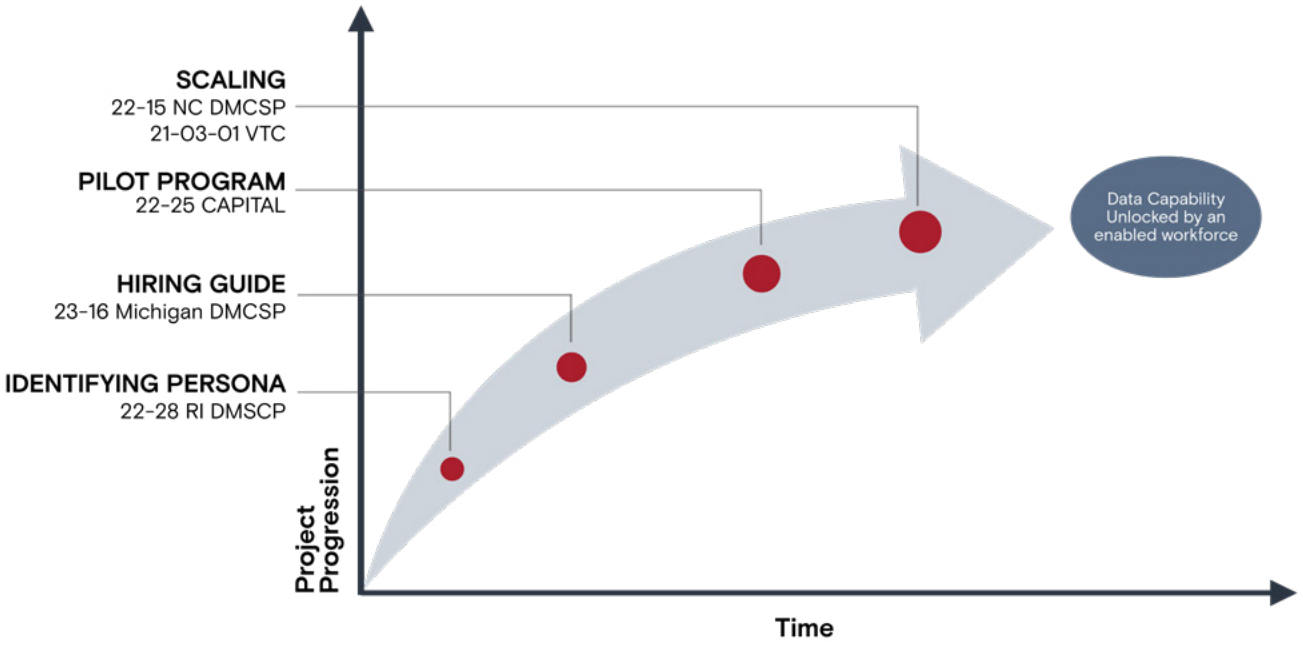


Figure 17: Workforce Project Progression to Scale Upskilling Resources



Workforce development projects do not fall directly within the context of the data lifecycle framework. In workforce development, the data lifecycle is inherent in what the workers do. As such, a workforce that is trained in and understands the importance of the quality and fidelity of the data it interacts with during the manufacturing process is an integral part of leveraging data to unlock business solutions.

ACTIVE WORKFORCE DEVELOPMENT PROJECTS

22-15 North Carolina State University Industry Expansion Solutions

Through the U.S. Department of Defense Office of Local Defense Community Cooperation, $5 million was granted to the North Carolina State University Industry Expansion Solutions-led Defense Manufacturing Consortia to undertake a project around advanced textiles/autonomous wearables and implement a strategy to address immediate ramp-up needs as businesses transition out of COVID-19 restricted operations to longer-term technological opportunities.

The project will take place over five years, and MxD Learn is currently leading the implementation. As part of the effort, MxD Learn provides advisory services and guidance regarding cybersecurity aspects of connected machines and technologies and ensures efforts in North Carolina are aligned with national trends in digital manufacturing efforts. Throughout the project, MxD Learn will explore the use of the VTC as a platform for disseminating outcomes in workforce development content solutions and cybersecurity for manufacturing tools.

22-25 MxD Learn CAPITAL – Curriculum and Pathways Integrating Technology and Learning (FY22 Federal Workforce Development Appropriations)

MxD Learn was awarded funding through the federal appropriations process, sponsored by Senator Richard Durbin, to develop certification-based workforce training programs for future manufacturing jobs, particularly in digital manufacturing and cybersecurity for manufacturing, necessary to strengthen the DIB. These courses, which will focus on urgent current and emerging workforce needs, will support foundational roles that allow workers to grow in meaningful careers and enable employers to adopt emerging technologies for use within their facilities. Additionally, focusing on foundational-level roles enables MxD to share the content with a broad audience including academia for its use, dissemination, and adoption.

Work is underway with a series of phases, including R&D that builds off the existing Hiring Guides, further development of roles and career pathways, development of curriculum to accompany roles and pathways, porting curriculum to MxD Learn VTC, and training program pilots. The successful execution of this program will result in new career pathway plans, new certification-based role curricula that train workers for the most critical emergent skillsets in the manufacturing sector, courses and content available to academic partners, and a more robust and more secure DIB.

22-28 Rhode Island Manufacturing to Accelerate the Defense Ecosystem (RI MADE)

Through the U.S. Department of Defense Office of Local Defense Community Cooperation, the University of Rhode Island Research Foundation was awarded $5 million to address weaknesses in the maritime defense industrial base through strengthening workforce training or retraining or recruitment and retention, and expanding small business assistance to support automation, robotics, and cyber resiliency. The project will provide intensive technical assistance to a minimum of 25 small businesses, educate and train 675 students and workers using MII enhanced offerings, and launch an innovative “education to assessment” model to enhance assessment capability and supplier matching for DoD supply chain companies.

MxD Learn supports this initiative as a sub-recipient to the University of Rhode Island. MxD Learn will develop and implement a CMMC train-the-trainer program that the Polaris MEP will use to assess CMMC compliance at manufacturers and suppliers. Further, MxD will serve as a subject matter expert and provide one-on-one support to Rhode Island manufacturers on cybersecurity and CMMC

compliance. This project will take place over five years and help secure the defense industrial base.

23-16 Michigan DMCSP

As a member of the Michigan Defense Resiliency Consortium (MDRC), MxD will develop an Electric Vehicle (EV) Hiring Guide that outlines the knowledge, skills, and abilities necessary to be successful in roles in the EV supply chain — with a section focused on roles in energy storage and battery supply chains. Subject matter experts and MDRC member input will inform the guide and include recommendations for credentialing to fill the targeted roles.

MxD will also develop a Community Equity Plan to highlight pathways for underserved communities in Michigan to leverage the investment from the DoD's Defense Manufacturing Community Support Program (DMCSP) and participate in working and fulfilling skills in the EV sector. The Community Equity Plan will acknowledge the transition from internal combustion engine (ICE) manufacturing to EV manufacturing and how current ICE workers can reskill to join the EV workforce. Additionally, a community equity plan will detail barriers experienced by underserved and marginalized communities that prevent them from participating in the EV sector in Michigan.

Emerging Technology

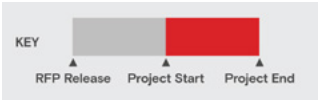


Figure 18: Emerging Technology Project Timelines

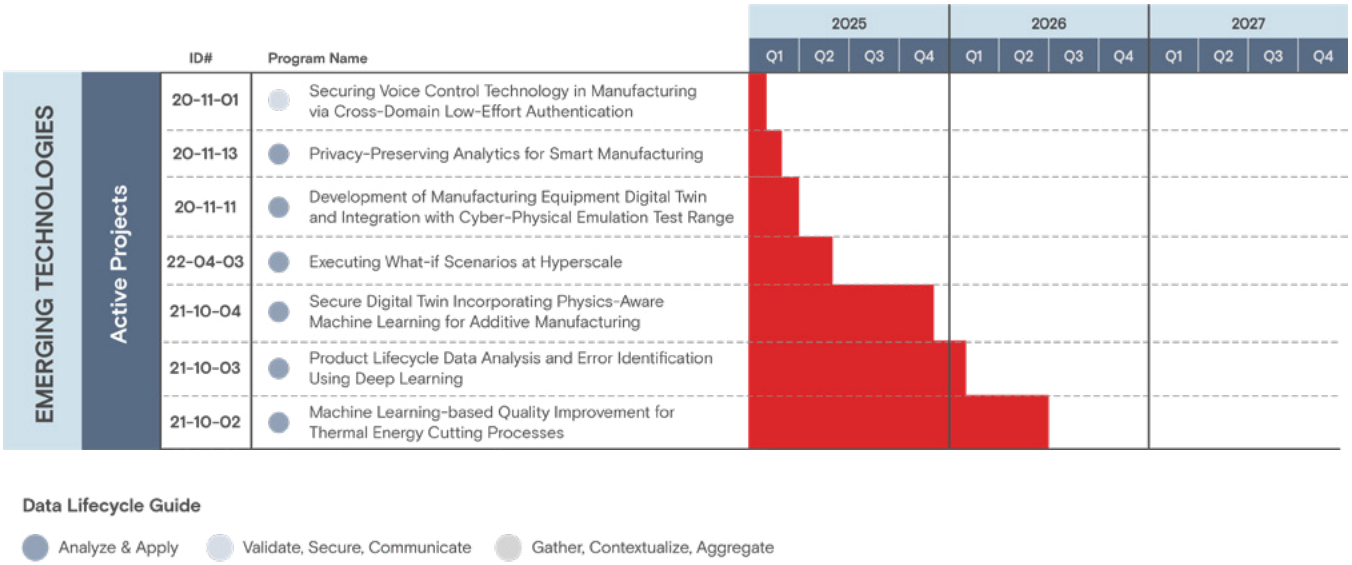
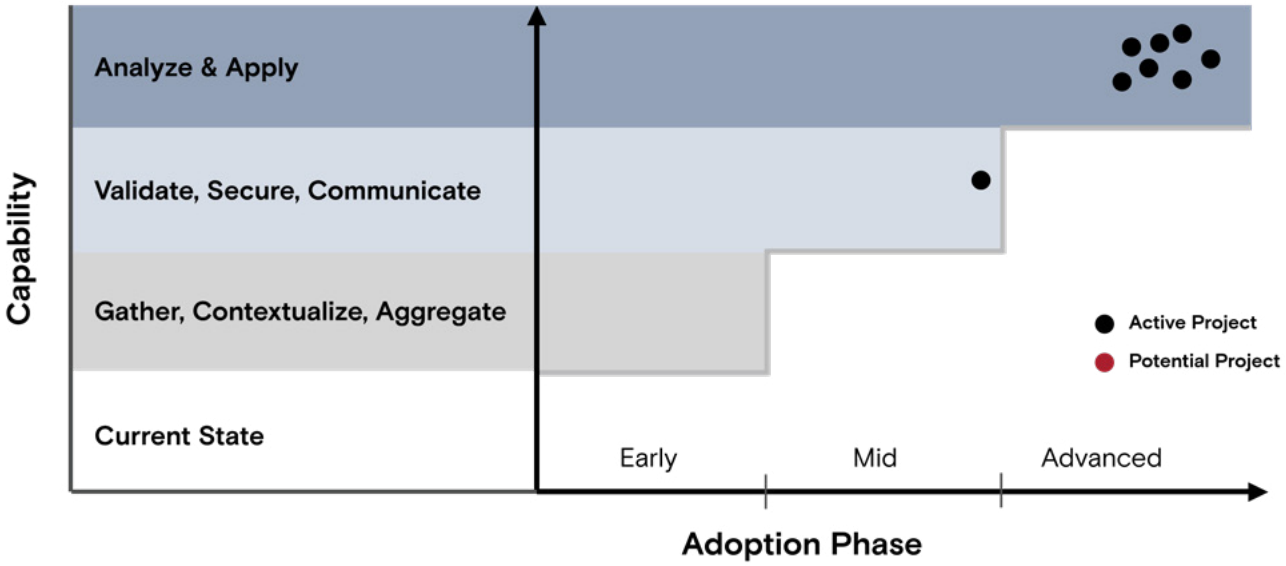


Figure 19: Emerging Technology Project Distribution with Respect to the Data Capability Framework



ACTIVE EMERGING TECHNOLOGIES PROJECTS

20-11-01 Securing Voice Control Technology in Manufacturing Via Cross-Domain Low-Effort Authentication

Project Team: Texas A&M University, Rutgers University

As voice-assisted AI assistants such as Apple's Siri and the Amazon Echo ("Alexa") have revolutionized how consumers perform daily tasks, similar applications are widely adopted and deployed throughout manufacturing. However, the convenience of using voice control in factories also opens the door to adversaries seeking access to a company's critical information and controls. With unauthorized access, attackers can make equipment malfunction, create faulty products, or completely disrupt operations.

Instead of using traditional approaches in the audio domain to defend against attacks, this project will explore capturing voice commands in another domain (e.g., vibration domain) and then performing cross-domain authentication. This project will advance the security of voice control technology in manufacturing by using cross-domain sensing capabilities to enhance user authentication. New software will be available to deploy, and further signal processing and machine learning techniques will be developed to study various sensing signals.

20-11-11 Development of Manufacturing Equipment Digital Twin and Integration with Cyber-Physical Emulation Test Range

Project Team: University of North Carolina at Charlotte

The techniques used to assess the cybersecurity of enterprise networks are not always practical when assessing manufacturing floor networks and equipment. Unlike corporate networks, factory floor networks typically consist of personal computers and Industrial Control Systems (ICSs). There is an urgent need to evaluate how sophisticated cybersecurity attacks can compromise equipment connected to ICSs. Manufacturing networks with supervisory control and data acquisition (SCADA) devices — directly interacting with equipment sensors, valves, pumps, and motors — are often insecure, making them desirable targets for cyber attackers.

This project will develop a manufacturing equipment digital twin (MEDT) using commercially available modeling software. This digital twin will be a virtual replica of physical manufacturing equipment. The team will integrate this digital twin with a previously developed cyber-physical emulation test range and subject it to malicious traffic and other simulated attacks. This will allow real-time evaluation of the equipment's performance under various cybersecurity scenarios — while keeping everything safely separate in the virtual world.

20-11-13 Privacy-Preserving Analytics for Smart Manufacturing

Project Team: Penn State University, Siemens

This project will develop a new privacy-preserving technique, Mosaic Gradient Perturbation (MGP), to reduce the risk of model inversion attacks in manufacturing applications. The proposed approach will capitalize on the power of data analytics to protect data privacy and build smart manufacturing systems. In addition, the goal is to develop a distributed computing version of privacy algorithms for the IIoT space.

Intelligent agents (e.g., machines, AGVs, and sensors) interconnect and communicate in the new generation of smart factories. AI models of manufacturing agents are not limited to predictive models but also generate autonomous learning models called reinforcement learning. Privacy and security concerns arise because AI collects agents' dynamic operational and environmental data. Attack types are categorized into privacy-leaking attacks and adversarial attacks. Privacy-leaking attacks target information in the environment, and data breaches lead to an enormous loss of revenue. Also, hostile attacks damage the environment, causing AI models to result in errors in the system. When AI models of manufacturing agents are compromised, this significantly disrupts

the autonomous manufacturing system and operational management. Therefore, the objective of the Year 2 project is to develop privacy-preserving distributed AI models that make manufacturing smart and secure. The MGP algorithm developed in Year 1 will be enhanced to protect distributed AIs and mitigate privacy-leaking attacks. Because AI mechanisms consist of deep neural networks, the MGP algorithm from Year 1 lays a solid foundation for this Year 2 project. The team will further develop new mechanisms to protect AI state and action spaces and mitigate risks of inference about the environment. To tackle adversarial attacks, the AI model will modify its objective function by the AI perturbation method. This method will provide robustness to AI models against malicious attacks that lure the agent to a designated target state.

21-10-02 Machine Learning-based Quality Improvement for Thermal Energy Cutting Processes

Project Team: Northern Illinois University

This project will develop and validate a smart digital tool that automatically collects process and quality data and uses the data to provide process control feedback directly to the operator and process planner to assist with part quality control for a manufacturing process. Quality control in manufacturing processes is a critical challenge for many industries. Reducing defect rates can lead to positive outcomes in cost reduction throughput improvement, ultimately elevating the industry's competitiveness. For a long time, quality control has relied on time-consuming manual or semi-manual approaches, in which a large amount of valuable data is lost. Additionally, it takes extra steps to finalize and execute manufacturing process adjustment decisions to resolve quality issues. This project will provide an overview of the systematic design of this tool, the plans for implementing it, and finally, validating it in an industrial environment.

21-10-03 Product Lifecycle Data Analysis and Error Identification Using Deep Learning

Project Team: Penn State University Applied Research Lab, Siemens

PLM systems manage a lot of data about a product's lifecycle, including CAD models, drawings, and specifications. That data has many different formats depending on the software from which it originated. As a result, using a PLM system as a data repository can mean hundreds of thousands of files in heterogeneous formats. The volume of data and the lack of standardization require automated pruning. That pruning will decrease duplication, making it difficult to find previously designed components and cutting the information technology costs needed to manage the infrastructure supporting the data and software. This project will develop a topography of PLM features and corresponding pain points that prevent standardization and use these findings to create a deep-learning model that can detect anomalies. This will inform the development of a transfer model and implementation pipeline so that anomaly detection and data analysis can be shared among manufacturers without compromising any single company's data privacy.

21-10-04 Secure Digital Twin Incorporating Physics-Aware Machine Learning for Additive Manufacturing

Project Team: Iowa State University, DMI Inc.

Complex manufacturing systems can be improved by implementing digital twins that monitor, predict, and detect disturbance, thus reducing risk. Recent technological advances allow manufacturers to analyze their capabilities in real time and plan for what-if scenarios. This project will develop and deploy a near-real-time digital twin framework to securely, reliably, and efficiently achieve the best part quality and desired graded material microstructure. The digital twin will leverage physics-aware machine learning capabilities to connect sensor and process parameter output to microstructure and properties, high-speed graphics processing unit (GPU) computing to enable real-time control, and cybersecurity principles to support trust/assurance and provenance in manufacturing line security.

22-04-03 Executing What-if Scenarios at Hyperscale

Project Team: Arizona State University

This project will develop and demonstrate an approach for executing what-if scenarios (aka

counterfactuals) at hyperscale in virtual manufacturing machines to perform root cause analysis (RCA). The project team will conduct these counterfactuals in virtual factories powered by a physics-based Unreal Game Engine running on Nvidia-powered GPUs that can provide a real-time 3D rendering and simulation of the dynamic state of the physical assets, simulate surface textures of finished parts, and incorporate sensory information relatable to human operators.

Hyperscale execution of what-if scenarios in virtual factories will allow process engineers to test hundreds of thousands of competing hypotheses simultaneously without requiring them to interact with machines in the physical world. This emerging technology would provide a new approach to replace the traditional RCA that often requires a dedicated team of operators and subject matter experts to resolve.

Appendix A:

2025-2027 Capability Advancement Roadmaps

The figures below represent MxD's technology strategy via project roadmaps that transcend the conventional project categories of Design, Future Factory, Supply Chain, etc., and focus on maturing and scaling a particular capability into a viable novel business solution.

In the future, we will use capability advancement roadmaps to showcase our strategic planning and progress made in responding to demands for specific capabilities from our members, partners and broader industrial base. These roadmaps will be shaped by the outcomes of previous MxD projects and the needs expressed by our members.

Over the past decade, we have evaluated demand for capabilities and identified overarching themes through surveys, individual discussions, and outreach. These themes represent the current state and highlight areas where further progress in developing business solutions is necessary.

It is important to note that capability advancement roadmaps do not undermine the significance of projects that provide specific solutions or address individual use cases. They also do not indicate a shift away from such projects. Instead, they recognize the importance of advancing manufacturing technology at both the industry-wide and individual worker levels.

CAPABILITY ADVANCEMENT ROADMAPS

Maturity Assessment: A maturity assessment is a comprehensive evaluation of a manufacturer's current capability state, including its digital and operational maturity. Digital manufacturing emphasizes the integration of cyber-physical systems, the IoT, and advanced data analytics. As such, a maturity assessment serves as the foundational first step toward effective strategic digital planning.

MxD is committed to supporting manufacturers as they assess where they stand regarding technological adoption and process optimization so they can identify gaps, prioritize investments, and tailor their digital transformation strategies to enhance productivity and competitiveness to meet their needs. This approach ensures that digital initiatives align with the company's objectives and facilitate a smooth transition toward a more connected, intelligent, and automated production environment, ultimately driving innovation and growth in the rapidly evolving manufacturing landscape.

Figure 20: Maturity Assessment Project Timelines

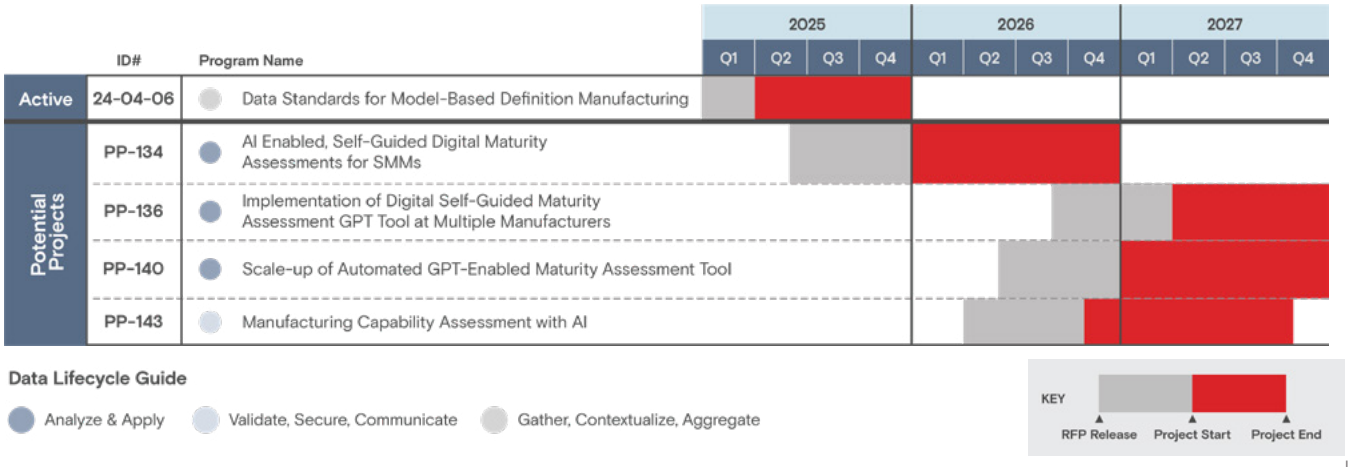
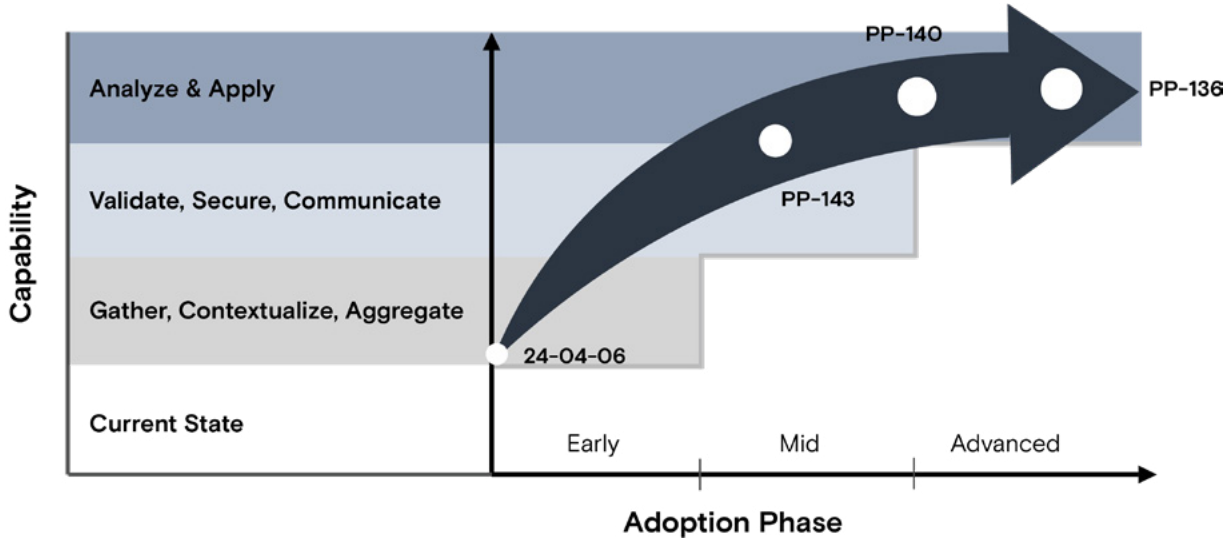


Figure 21: Maturity Assessment Project Progression Toward Capability Maturity with Respect to the Data Capability Framework



Data Standards, Architecture, and Interoperability: The successful implementation of digital manufacturing relies heavily on data standards, architecture, and interoperability, as MxD has learned through engagement with the industrial base. As factories transition into intelligent, interconnected systems, the importance of a standardized approach to data cannot be overstated. Consensus on the essential data requirements, format, and structure is necessary for ensuring seamless compatibility across diverse systems and software. This harmonization facilitates communication among machines, sensors, and platforms, enabling real-time data exchange and analysis. Such interoperability enhances operational efficiency and productivity, allowing manufacturers to harness advanced technologies such as the IoT, AI, and ML. Ultimately, these standards form the basis for a more agile, responsive, and competitive manufacturing environment, driving innovation and sustainability in an increasingly digital world.

Figure 22: Data Standards, Architecture, and Interoperability Project Timelines

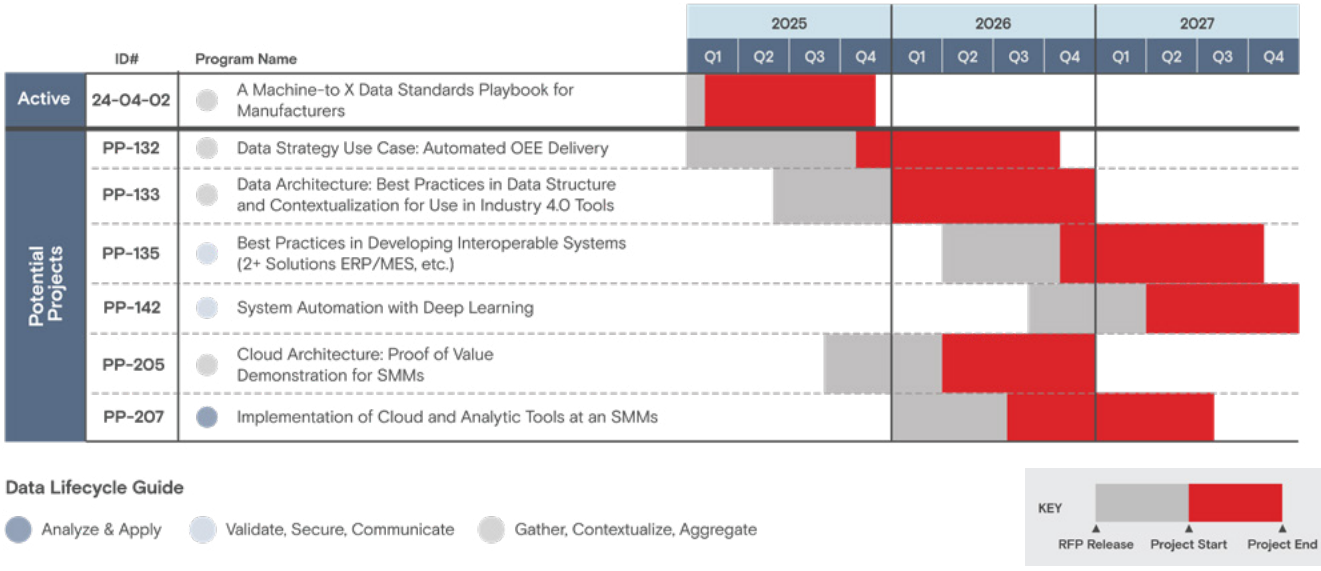
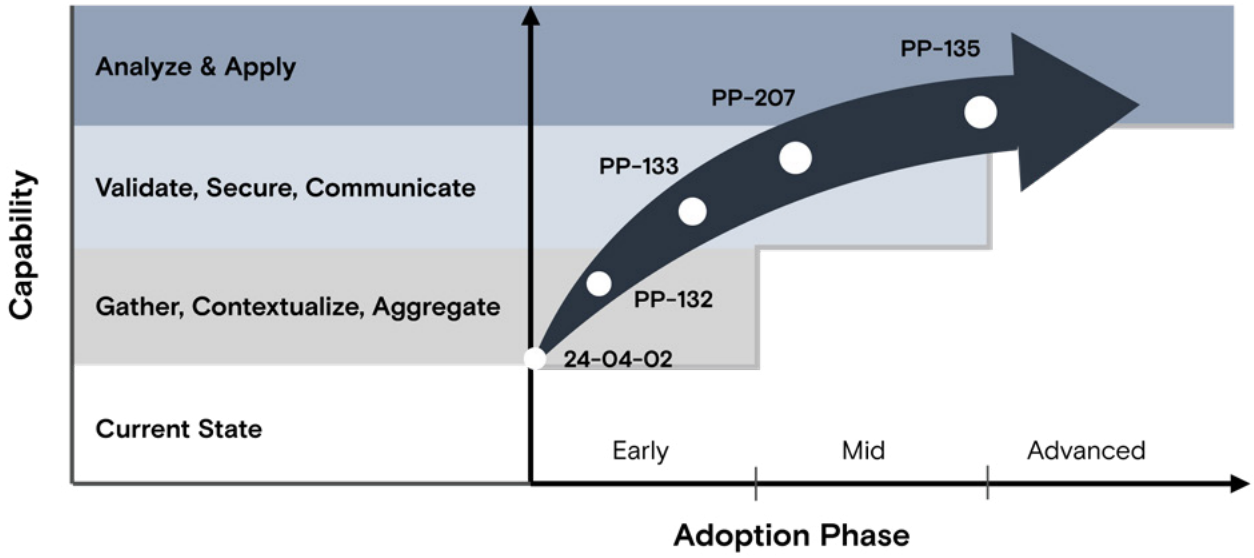


Figure 23: Data Standards, Architecture, and Interoperability Project Progression Toward Capability Maturity with Respect to the Data Capability Framework



Digital Twin: In digital manufacturing, digital twins have emerged as a revolutionary tool, transforming how industries approach production processes. Companies can perform detailed analyses and optimizations of their systems without disrupting production by creating highly accurate simulated models of physical manufacturing operations. This innovative approach allows manufacturers to identify inefficiencies, predict maintenance needs, and test the impact of potential changes in a virtual environment, thus mitigating risks and reducing downtime. However, the true power of digital twins lies in their ability to enhance the precision and efficiency of manufacturing processes and drive continuous improvement and innovation — a foundational principle that MxD looks to provide. Therefore, by sharing expertise and providing a platform for testing and refining new ideas, MxD digital twins will pave the way for a smarter, more resilient industrial base.

Figure 24: Digital Twin Project Timelines

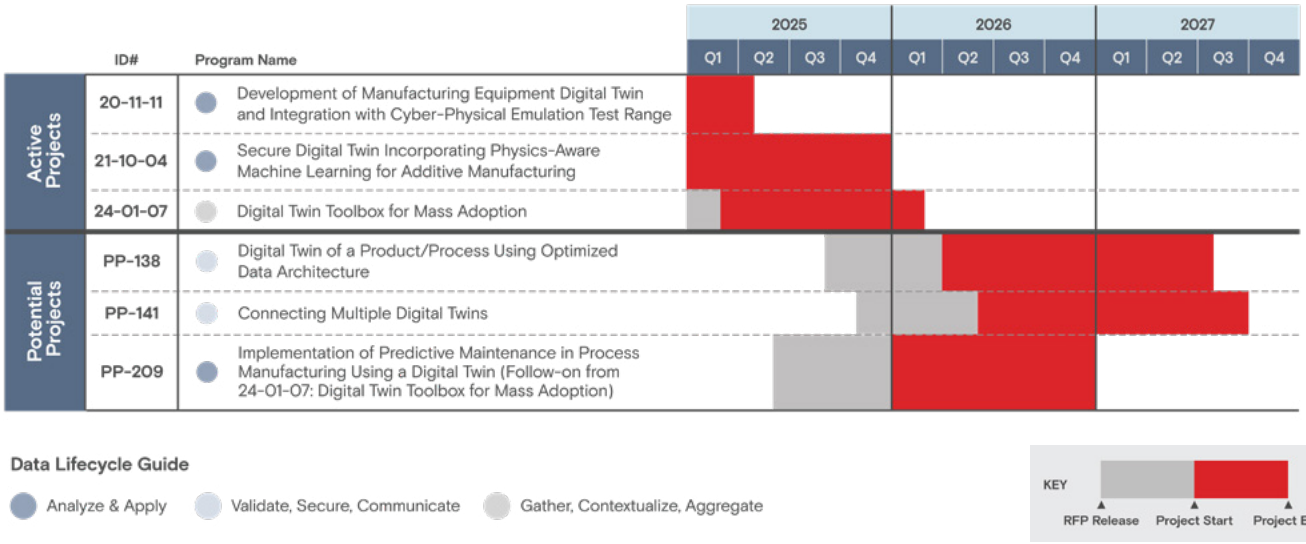
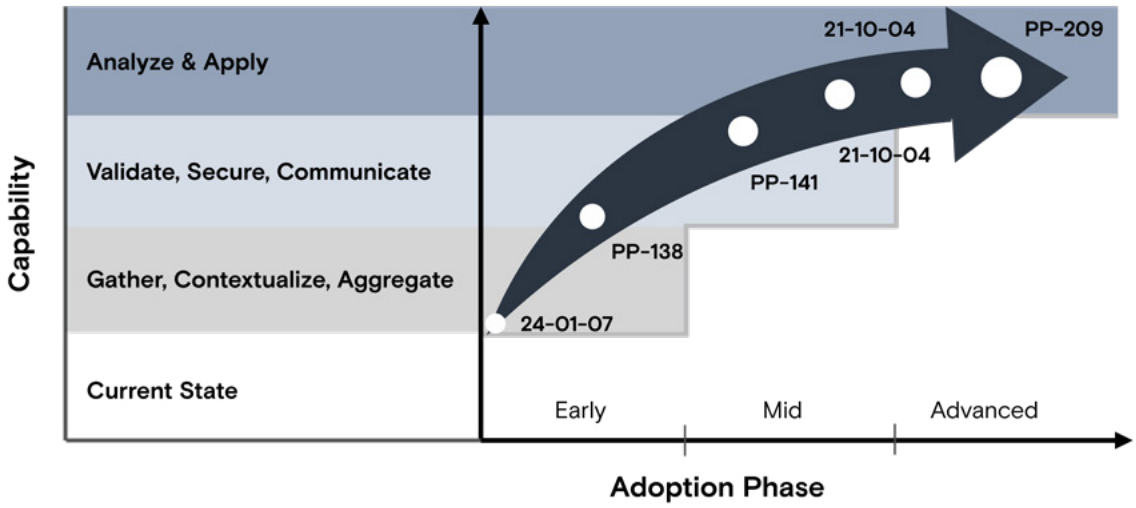


Figure 25: Digital Twin Project Progression Toward Capability Maturity with Respect to the Data Capability Framework



Supply Chain Visibility: MxD seeks to drive data integration across supply chains to streamline people and processes, which is fundamental in digital manufacturing. In an era where agility and efficiency are paramount, digital manufacturing leverages advanced technologies to achieve seamless data integration across various supply chain stages. Visibility across supply chains ensures that every stakeholder, from supplier to manufacturer to distributor, operates with real-time insights, enabling proactive decision-making and reducing bottlenecks. By streamlining people and processes, digital manufacturing enhances operational efficiency and fosters a collaborative environment where transparency and communication are prioritized. As a result, companies can respond swiftly to market demands, optimize resource allocation, and ultimately deliver higher-quality products to consumers more efficiently. This holistic approach underscores the transformative impact of digital manufacturing on modern supply chains, driving innovation and competitiveness in a rapidly evolving market landscape.

Figure 26: Supply Chain Visibility Project Timelines

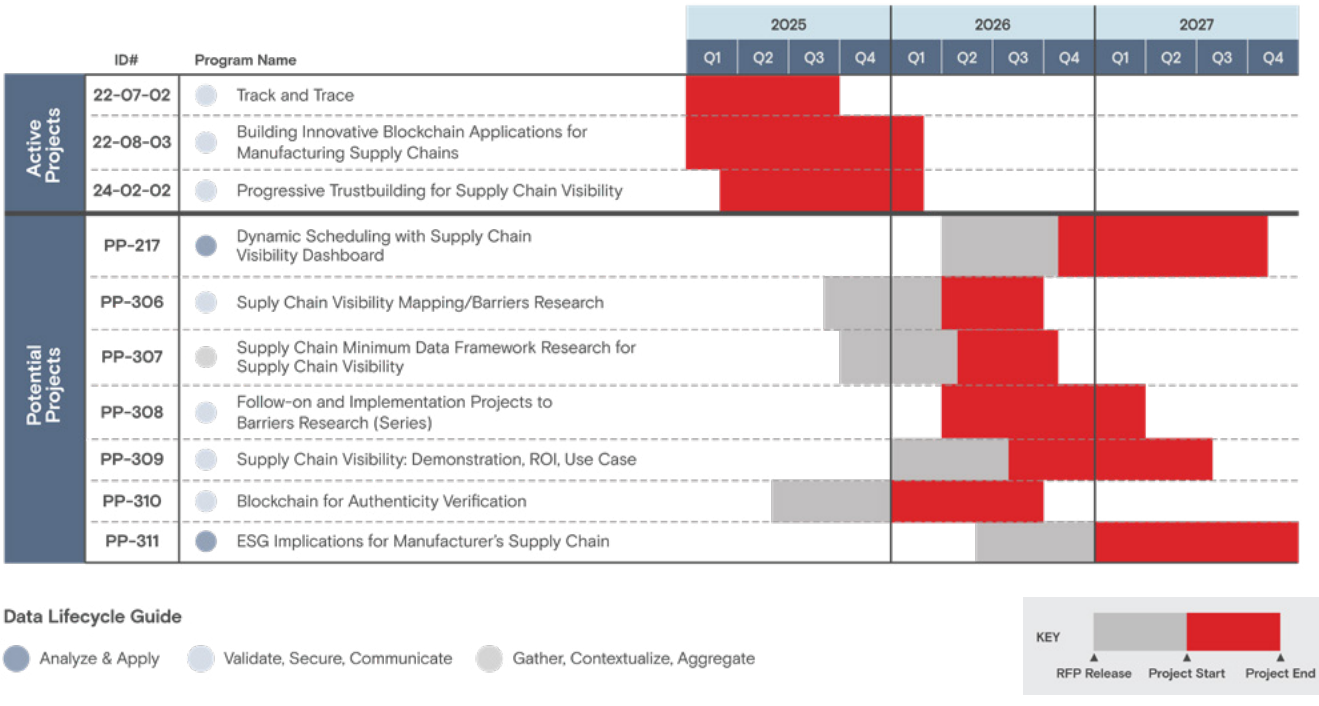
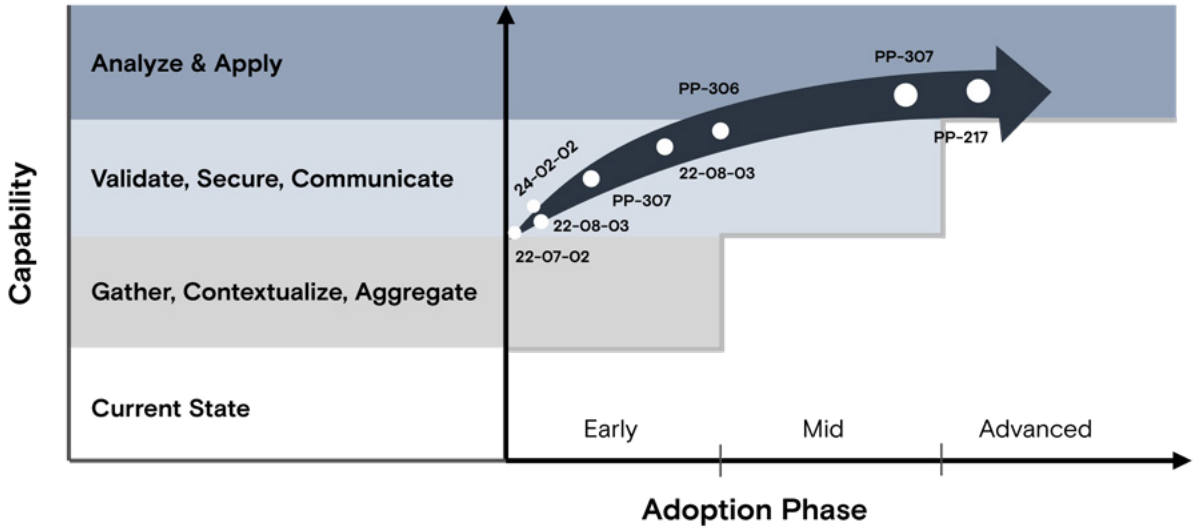


Figure 27: Supply Chain Visibility Project Progression Toward Capability Maturity with Respect to the Data Capability Framework



Digital Adoption: The digital transformation is not just a trend. It's a necessity. It is also an imperative to increase the incentive to adopt digital manufacturing by maximizing the potential ROI, ensuring that U.S. manufacturers remain competitive and resilient in a rapidly evolving market landscape. By facilitating access to digital tools and strategies, MxD looks to enhance operational efficiency, optimize production processes, and innovate product development, ultimately helping manufacturers drive growth and sustainability. Moreover, as OEMs lead the push toward digital, their embrace of digital transformation allows upstream manufacturers to integrate seamlessly into their smart manufacturing network, where real-time data exchange and automation can lead to improved supply chain management and customer satisfaction. Thus, addressing the challenges to digital adoption empowers businesses to thrive and contributes to the broader economic landscape by fostering innovation and productivity.

Figure 28: Digital Adoption Project Timelines

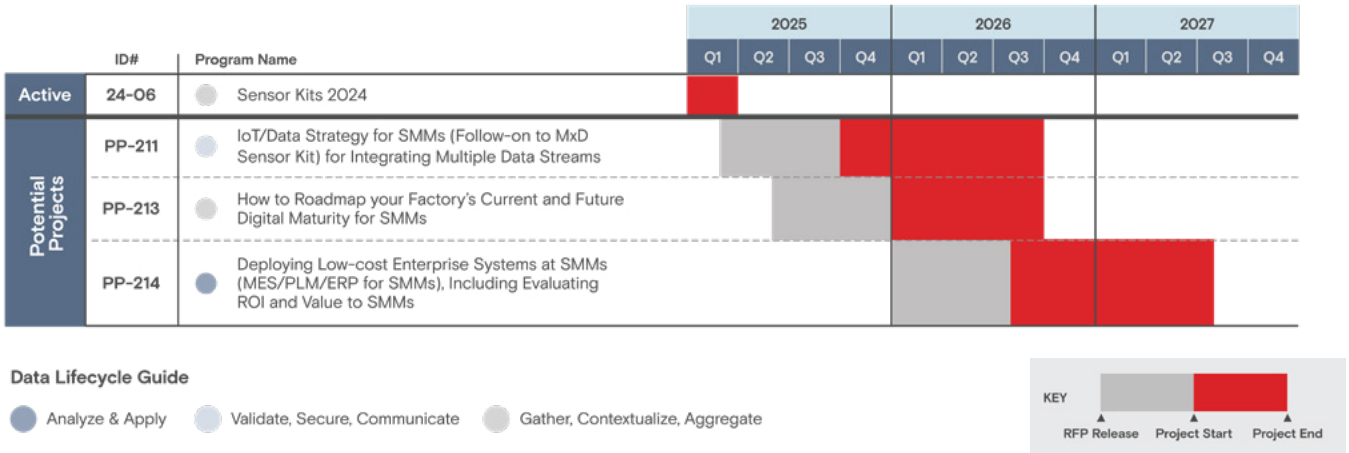
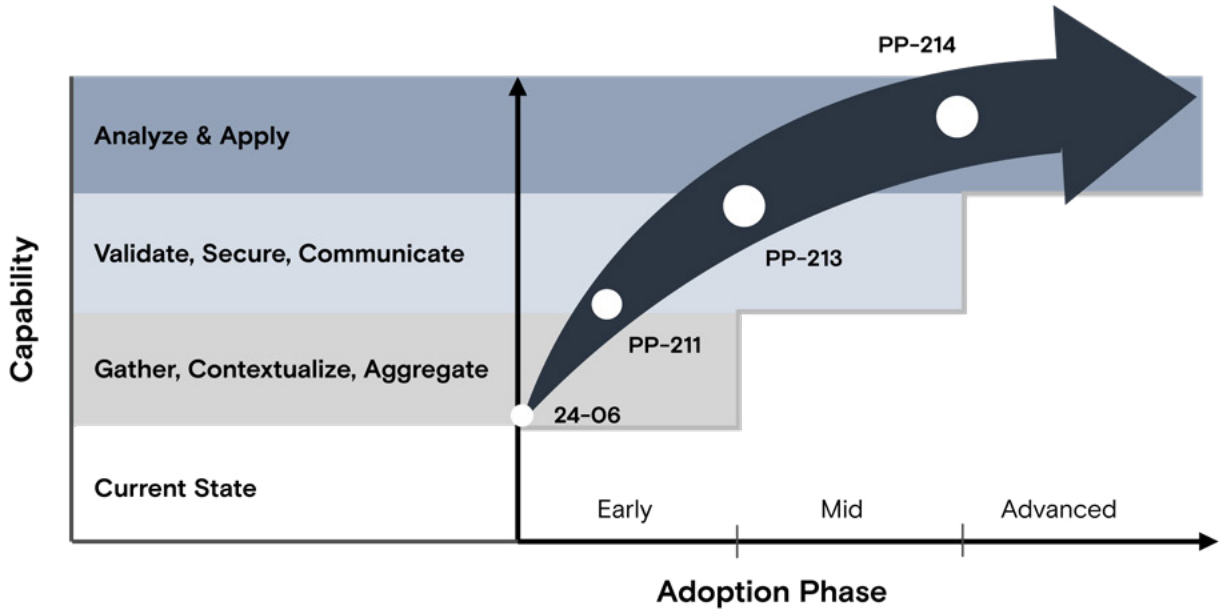


Figure 29: Digital Adoption Project Progression Toward Capability Maturity with Respect to the Data Framework



Advanced Data Capability Solutions: As MxD works to provide tools to enable digital adoption efficiently and remove barriers for manufacturers, advanced data capability solutions are invaluable for spurring innovation and enabling large manufacturers to advance their digital maturity. Once a mature data lifecycle has been established, these solutions provide the foundation for identifying and implementing use cases that significantly enhance manufacturing operations. By leveraging robust data analytics, manufacturers can achieve greater insights into their processes, leading to improved decision-making, enhanced efficiency, and reduced operational costs. Furthermore, the ability to analyze data in real time allows for predictive maintenance, minimizing downtime and extending equipment lifespans. As these advanced solutions uncover patterns and trends, they enable manufacturers to innovate by optimizing product designs and customizing offerings to meet evolving market demands. In essence, these solutions transform data into a strategic asset, driving continuous improvement and positioning manufacturers at the forefront of the digital transformation journey.

Figure 30: Advanced Data Capability Solutions Project Timelines

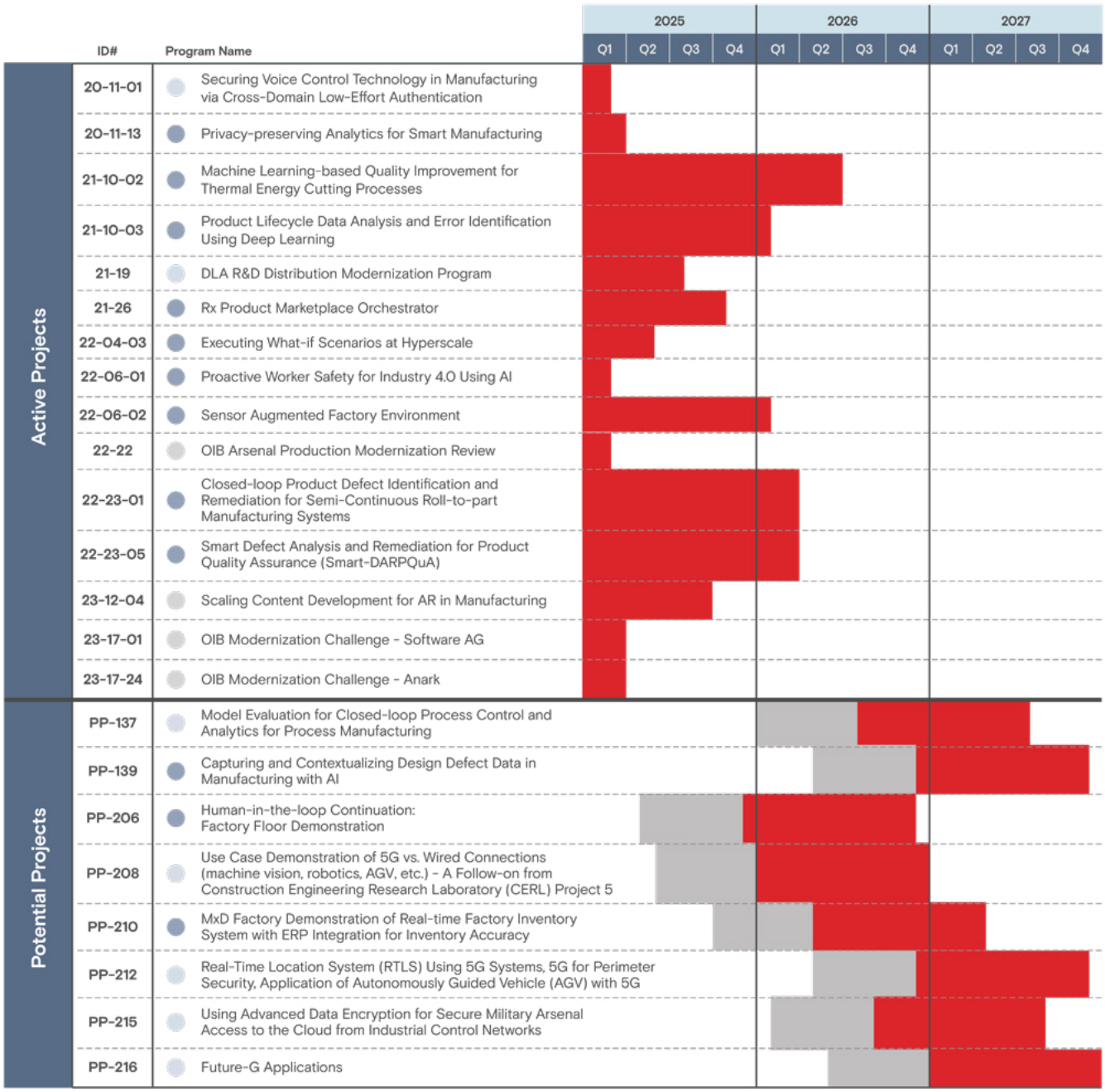


Table of Acronyms

AFRL: Air Force Research Lab
AGV: Autonomously Guided Vehicle
AI: Artificial Intelligence
AMC: Army Materiel Command
AR: Augmented Reality
CAD: Computer-Aided Design
CAPITAL: Curriculum and Pathways Integrating Technology and Learning Program
CBRS: Citizens Broadband Radio Service
CERL: Construction Engineering Research Laboratory
CMMC: Cybersecurity Maturity Model Certification
COTS: Commercial Off the Shelf
CUI: Controlled Unclassified Information
CyMOT: Cybersecurity for Manufacturing Operational Technology
DCN: Distributed Control Node
DERISC: Digital Education, Resilience, and Innovation for Supply Chain
DIB: Defense Industrial Base
DLA: Defense Logistics Agency
DMCSP: Defense Manufacturing Community Support Program
DME: Digital Manufacturing Enterprise
DoD: Department of Defense
DTC: Digital Twin Consortium
ERP: Enterprise Resource Planning
ESG: Environmental, Social, and Governance
EV: Electric Vehicle
GPT: Generative Pre-Trained Transformer
GPU: Graphics Processing Unit
ICE: Internal Combustion Engine
ICS: Industrial Control Systems
IIoT: Industrial Internet of Things
IoT: Internet of Things
IT: Information Technology
JDMTP: Joint Defense Manufacturing Technology Panel
ManTech: Manufacturing Technology
MBE: Model-Based Engineering
MDMC: Marine Depot Maintenance Command
MEDT: Manufacturing Equipment Digital Twin
MEP: Manufacturing Extension Partnership
MES: Manufacturing Execution System
MGP: Mosaic Gradient Perturbation
MII: Manufacturing Innovation Institute
ML: Machine Learning
MOM: Manufacturing Operations Management
NIST: National Institute of Standards and Technology
OEE: Overall Equipment Efficiency
OEM: Original Equipment Manufacturer
OIB: Organic Industrial Base
OPAF: Open Process Automation Forum
OSD: Office of the Secretary of Defense
OT: Operational Technology
PLC: Programmable Logic Controller
PLM: Product Lifecycle Management
PP: Potential Project
R&D: Research and Development
RCA: Root Cause Analysis
RFP: Request for Proposal
ROI: Return on Investment
RTLS: Real-Time Location System
SAFE: Sensor Augmented Factory Environment
SCRMC: Supply Chain Risk Consortium
SCSP: Special Competitive Studies Project
SIP: Strategic Investment Plan
SMMs: Small and Medium Manufacturers
SPC: Statistical Process Control
TAC: Technology Advisory Committee
TDP: Technical Data Package
VTC: Virtual Training Center
WMS: Warehouse Management System
XR: Extended Reality

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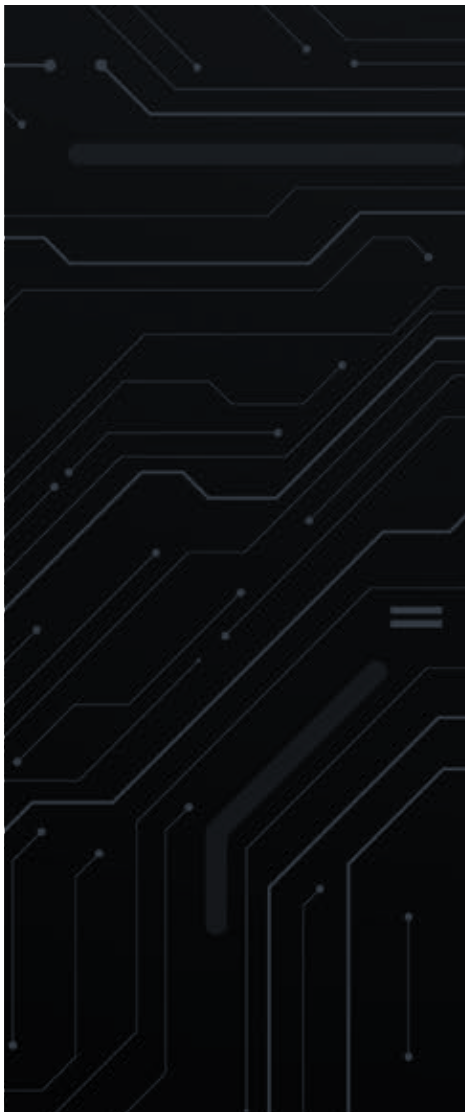

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