Symposium: Strategy for Resilient Manufacturing Ecosystems Through Artificial Intelligence

Report from the Third Symposium Workshop

National Program Strategies and Roadmap to Scale the Adoption of AI in Advanced Manufacturing

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Executive Summary

The National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST) sponsored a three-workshop Symposium entitled, "Strategy for Resilient Manufacturing Ecosystems Through Artificial Intelligence." **Workshop 1**, held in December 2020, identified four key areas for adoption of AI in manufacturing that are synergistic with the growing foundations of manufacturing digitalization. **Workshop 2**, conducted as a series of four roundtable discussions held in June and July 2021, defined three goals as focal points to overcome the greatest barriers to AI adoption. **Workshop 3** consisted of three roundtables held in February 2022. Using the results of the prior two workshops, Workshop 3 produced an actionable roadmap and recommendations for specific R&D strategies, government programs, and industry actions that can initiate and accelerate the adoption of AI.

Following 40 years of progress in digital data in the manufacturing industry, Smart Manufacturing/ Industry 4.0 has been building in interest and adoption for 15 years. Unfortunately, the U.S. manufacturing industry is pursuing digital transformation with an incremental approach, risk posture, and pace comparable to that of the past 40 years. The Symposium emphasized the potential for the application of AI in manufacturing to provide a world-leading advantage to the U.S. manufacturing industry that justifies a much faster pace of research and development, skills and tools development, and industry adoption. Such a broad transformation will encompass structural business change that accommodates industry-wide strategies to apply AI and achieve its full competitive value. With data and IT capabilities changing at an increasingly rapid pace, and other countries investing in digitalization and competitiveness, the workshops tackled a fundamental question of how to accelerate both technology change and market-driven business models in the U.S. The manufacturing industry is not fundamentally opposed to the adoption of AI technology, or the basic changes in business models the technology will inevitably create. On the contrary, many large corporations and a few Small and Medium Manufacturers (SMMs) are currently working to incorporate AI technology into their operations. However, the adoption of AI is complicated by limitations in capabilities at SMMs, the significant need for R&D, a lack of scalable successes, and the need to build business trust in new ways. Unless several key challenges can be overcome, the benefits of advanced AI systems in the hierarchy of manufacturing operations will remain incremental at best.

The roadmap presented in this report derives from the deliberations in all three workshops. It identifies multiple roles in which government programs have a key role to play in ensuring that the U.S. manufacturing industry leads the transition to an AI driven, digital future. Given the need for multi-disciplinary and multi-stakeholder collaboration among industry, academia, and government to take on industry-wide strategies, Public Private Partnerships (PPPs), for which there are many successful models, are the most appropriate coordinating structures. An opportunity exists to build on past PPP successes and adapt them to fit the requirements for AI adoption in U.S. manufacturing by involving all stakeholders in defining programs and funding requirements, supporting the implementation of programs and distribution of funds, and coordinating initiatives. The successes demonstrated by the actions of PPP coordination will reduce the risk of applying AI technologies in manufacturing operations, making it easier for entrepreneurs and private investors to visualize innovative operational products and business models. As this adoption cycle takes hold, the market-driven forces of entrepreneurship and investment capital will ultimately lead to industry-wide adoption of AI technology, and the U.S. manufacturing industry will be on its way to achieving global competitiveness and resilient supply chains.

Introduction

The National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST) sponsored a three-workshop Symposium entitled, "Strategy for Resilient Manufacturing Ecosystems Through Artificial Intelligence." This report and its recommendations are a compilation of inputs from all three workshops in the Symposium, including key areas for the use of AI in manufacturing, goals to overcome the greatest barriers to AI adoption, important priorities for research, development, and workforce education, an actionable roadmap, and recommendations for specific R&D strategies, government programs, and industry actions that can initiate and accelerate the adoption of AI. To obtain this information, the workshops brought together representatives from manufacturing companies, AI researchers and application developers, university faculty with manufacturing and AI expertise, government agencies, labs and programs, and the Manufacturing USA Institutes to address the essential requirements for broad, industry-wide adoption of AI technology in U.S. manufacturing. The questions discussed during the workshops included:

- Key roles for AI in manufacturing and how they can be monetized;
- Primary barriers to accelerating and scaling AI adoption;
- Software tools, training, and R&D required;
- Organization of the identified elements as programs in a national roadmap; and
- Requirements for implementing and coordinating a national research, development, and adoption cycle for AI in U.S. manufacturing.

> **Artificial Intelligence (AI)** in manufacturing refers to software systems that can recognize, simulate, predict, and optimize situations, operating conditions, and material properties for human and machine action.
> **Machine Learning** (generally seen as a subset of AI) refers to algorithms that use prior data to accurately identify current state and predict future state, with the goal of improving productivity, precision, and performance.
> **Models** are digital, software representations (quantitative, qualitative, pattern, causal, inference, etc.) of real-world events, systems, or behaviors, which can use data to simulate or predict future results.
> **Scale** means readily accessible, easy to use, and cost effective for manufacturers of all sizes.
> **Standard Data Format** refers to the organization of information (protocol) according to agreements on preset specifications that describe how data should be stored or shared for consistent collection and processing across different systems and users.
> **Tools** refer to software platforms that support the availability of data, knowhow, and models for use in business and operations.

Workshop 1 set the stage for the discussion by identifying seven key principles and the primary functions that need to be integrated to support an industry-wide strategy for realizing full value from and wide adoption of AI in manufacturing.

Workshop 2 brought full clarity to the potential for AI to penetrate nearly every aspect of the manufacturing industry and identified three goals for AI adoption that can overcome key barriers. The goals provided critical direction for Workshop 3:

- **Goal 1**: Enable Digital Capabilities at Small and Medium-Sized Manufacturers (SMMs)
- **Goal 2**: Incentivize AI Adoption Throughout Established Supply Chains
- **Goal 3**: Enable New Business Models for AI Adoption

Workshop 3 used these three goals as the basis for recommending an AI adoption roadmap. During each roundtable, the moderators reviewed one main goal and its subgoals with the participants and requested feedback to validate the completeness of the draft roadmap, steps to accomplish the goals and subgoals, and actions for implementation by government, industry, and academia. The resulting Roadmap provided a matrix of interrelated programs for accomplishing the three goals in efforts focused on addressing industry constraints, identifying new sources of revenue, and scaling success.

In validating the roadmap, four common themes emerged across all three goal discussions:

- Improved digital capability at SMMs was viewed as an absolute prerequisite for industry-wide adoption of AI and achievement of its full benefits.
- Structural business and technological limitations are inhibiting implementation of AI systems and execution of the roadmap.
- Broad adoption of AI will require new industry business models that accommodate widespread aggregation of data across manufacturers and access to advanced software tools with appropriate scale and cost for manufacturers of all sizes (i.e., software-as-a-service).
- Technologies required for robust, scaled, trustworthy AI in manufacturing are at a nascent stage and require continued R&D investment and coordination with existing research programs.

Within these common themes, roundtable discussions focused on the current barriers to AI adoption, and significant input formed around seven structural constraints. Participants recommended that execution of the AI adoption roadmap should start with actions to address these constraints, with a particular focus on SMMs, R&D, trust, and scalability. The following constraints and associated actions emerged:

1) Agree on establishing standardized data formats and repositories to store data to get started
2) Create an exchange platform for access to AI data, tools, models, and information
3) Provide financial incentives for SMMs to upgrade digital capabilities
4) Build educational programs at academic institutions and fund training at SMMs
5) Show value with use cases and provide blueprints for solutions at manufacturers of all sizes
6) Data enable legacy equipment that still has useful life, especially at SMMs
7) Allow ‘in-kind’ cost share for the value of the data provided by industry participants in government programs and institutes and make that data available to researchers

These constraints emerged as core barriers preventing many individual companies and their supply chains from participating in AI implementation programs. In practice, the seven structural constraints are linked together, and actions to address them require interrelated solutions. Targeted actions by government, industry, and academia are therefore required to address these interrelated problems and to coordinate the interaction of existing AI programs with new initiatives. While the immediate actions required will largely produce incremental progress in the use of AI, workshop participants suggested that incremental improvements will enable entry points for AI implementation and stimulate progress on the roadmap.

Execution of roadmap programs will necessarily begin with currently available technologies, which can provide immediate value. The Symposium stressed the importance of executing the roadmap with industry use cases and recommended starting an industry adoption cycle with a program that demonstrates that diverse manufacturing challenges can be addressed with an integrated set of ‘first pass’ actions on the seven constraints to demonstrate how business collaborations can succeed and produce value. A successful 'first pass' industry collaboration entails identifying initial use cases that apply AI to common manufacturing problems, provide demonstrations of the economic benefit of data sharing, produce first sharable "blueprints," and bring training together with basic tools. Expanding the execution of the roadmap in more complex use cases will require more advanced software tools, models, and infrastructure to enable the new business models required for scaling SMM digitalization and supply chain resilience. Recognizing these needs, the roundtables also identified four key R&D areas for future development programs:

- AI methods and data aggregation tools for manufacturing's dynamic data types
- Automation of algorithm building and continuous tuning
- Going beyond incremental industry change
- Scaling data and operational interoperability

Results from Workshops 1 and 2

Workshop 1, held in December 2020, identified four key areas of priority AI adoption that are synergistic with and build on a growing foundation of manufacturing digitalization (a.k.a, Smart Manufacturing/ Industry 4.0). The workshop emphasized the potential for untapped *productivity*, *precision*, and *performance*. Realizing the full potential of AI will require innovative technologies, services, and infrastructure for manufacturers to provide, with trust, the non-proprietary or protected domain data and knowhow needed to build and use AI for greater industry-wide interoperability, supply chain resiliency, new business models, and environmental sustainability. These strategies center on 'data sharing' (many forms), and application building, but also require substantial changes in organizations, markets, culture, technology risk, and business management. AI derives its power from more data than found in any one company. This is combined with industry learning how to scale and address AI to obtain significant benefits from intercompany data and operational interoperability. Longstanding industry practices on how data and operations are valued and compartmentalized currently work in opposition to these opportunities and need to change. If current industry practices remain unchanged, the competitive benefits of intra and intercompany (operational) interoperability and data sharing that comes with scaled AI adoption are expected to move forward slowly at best. Competitiveness that comes from speed of adoption is already stalling.

Workshop 2, conducted as a series of four roundtable discussions held in June and July 2021, focused on identifying the most important research, development, and workforce education priorities for industry-wide adoption of AI. It provided two important framing perspectives from which to build a Roadmap. First, three categories of monetization were identified and then used to distinguish three primary kinds of AI applications: (1) asset management on the factory floor, (2) interoperability between operating assets within factories and supply chains, and (3) intercompany interaction for supply chain resilience. These groupings of AI applications form three layers that also depend on each other: asset management depends on exploiting data; operational interoperability depends on asset management but also line operations and intercompany data interoperability; and supply chain resilience depends on data and operational interoperability as well as intercompany business visibility. These dependencies imply that manufacturers must act individually and together on resiliency strategies.

With respect to the role of industry interconnectedness: Layer 1, asset management, depends on industry data, knowhow, and application sharing in a brokerage of solutions targeted and discoverable for specific applications; Layer 2, interconnectedness, focuses on connecting data across operating assets within factories and across supply chains for greater operational interoperability; Layer 3, supply chain resilience, depends on the visibility and analysis of shared business data and in turn on the ability of individual manufacturers to act in concert. The workshop participants defined the functional requirements to be satisfied for each layer and identified three goals as areas of focus to guide development of an implementation roadmap.

Workshop 2 also categorized data in three different forms associated with each of the layers: data brokerage (sharing data to build software models for asset management), data exchange (exchanging data to increase operational interoperability), and supply chain data ecosystem visibility (exposing capacity and capability data for greater supply chain responsiveness). Operational technology and business technology performance tools to preserve privacy and security must be integrated in each of the three primary kinds of AI applications and for each form of data sharing. Furthermore, those tools need to be seamless across the layers so manufacturers can grow and readily move among the three layers of monetization. All of these tools depend on carefully building and managing trust in interactions between businesses, people, and machines. The human role in AI adoption is essential. For each manufacturer, business and operating tools, mechanisms of business exchange, and acquisition of skills through training and education need to align, a process that can only proceed at the pace of trust building and risk mitigation. These integrated operational and business tools encompass a large area of foundational R&D.

Workshop 2 identified a critical area of R&D associated with the complexities of collecting data and applying solutions at the location of deployment and source data when those solutions employ machine learning models generated from data aggregated from many manufacturers. A complex process is associated with the continuous learning that occurs as additional data is generated. There is also the need to appropriately partition that learning between the proprietary interests of the user and the shared interest of that same user in improving the capabilities of the underlying generic software model. This created a long-term R&D goal to create the software and communications framework needed to enable a trusted and dependable AI service provision infrastructure.

Workshop 3 Methodology and Roundtable Results

Workshops 1 and 2 both emphasized the potential of AI to penetrate every aspect of the manufacturing industry and produce significant economic impact. Numerous discussions highlighted strategies and R&D opportunities to address the challenges of using AI technology. Three primary goals were identified as foundational in addressing the most critical barriers impacting each of the three layers of monetization.

Workshop 3 used these three goals as the basis for recommending an actionable, AI adoption roadmap, including recommendations for specific R&D strategies, federal government programs, and industry initiatives that address the need for innovative technology, business policies, applications, software tools, training, and infrastructure to support AI adoption. Three roundtables were organized for Workshop 3 with one roundtable devoted to each goal. To stimulate roundtable discussions, a set of subgoals gleaned from Workshops 1 and 2 were developed for each of the three overall goals as follows:

Goal 1: Enable Digital Capabilities at SMMs

1. Overcome lack of resources, infrastructure, data, expertise, and administrative capacity
2. Enable SMMs to share data and knowhow for AI applications
3. Provide SMMs with tools to easily adopt AI solutions

Goal 2: Incentivize AI Adoption Throughout Established Supply Chains

1. Develop partnerships to define data, applications, and tools for supplier network interoperation
2. Enable companies to conduct demonstrations that define the value of scaled AI projects
3. Establish partnerships to converge on common AI applications and associated software tools and infrastructure

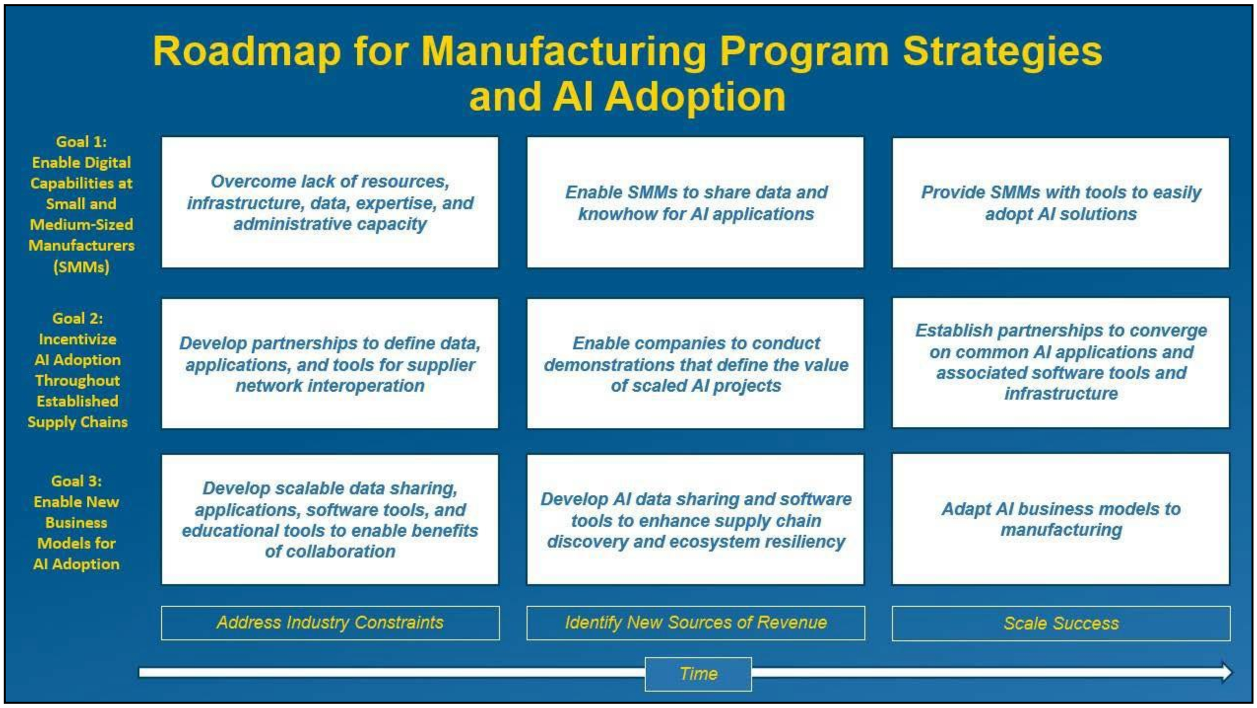
Goal 3: Enable New Business Models for AI Adoption

1. Develop scalable data sharing, applications, software tools, and educational tools to enable benefits of collaboration
2. Develop AI data sharing and software tools to enhance supply chain discovery and ecosystem resiliency
3. Adapt AI business models to manufacturing

The Workshop 3 roadmap was envisioned as a set of systematic recommendations for R&D, tools, training, and the distribution and coordination of industry, university, and government roles to overcome AI adoption barriers, accelerate the use of AI, and build a wave of momentum based on operational benefits. The roadmap addresses recommendations for AI adoption, not just within an individual factory, but across all operations of the industry and its supply chains. Importantly, the workshop focused not only on what should be included in a national roadmap, but also the roles of various key stakeholders, how they come together, and the execution and coordination of the roadmap. In acknowledging the U.S. preference for market-driven approaches, Workshop 3 raised questions around the aspects of the roadmap that require coordination, and the forms the coordination must take to best facilitate market-driven AI adoption.

Figure 1 charts the recommended goals and subgoals that constitute a logical roadmap and the program strategies, including the use of ongoing development cycles that build on activities and experience. The roadmap organizes national program strategies as a combination of industry, academic, and government activities all intended to accelerate the adoption of AI throughout the U.S. manufacturing industry. The subgoals in the white boxes are highly interrelated and each box represents an outcome or strategy that needs to be accomplished to implement the roadmap. As a result, the chart can be read from left to right **and** top to bottom.

Figure 1: Roadmap for Manufacturing Program Strategies and AI Adoption
(Figure can be read left to right **and** top to bottom)



During each roundtable, the moderators reviewed one main goal and its subgoals with the participants and requested feedback on (1) completeness of the information in the draft roadmap, (2) how to accomplish the goals and subgoals, and (3) specific actions to be considered by government, industry, and academia. The participants in each of the roundtables engaged in detailed discussions of the goals and actions that could contribute to achievement of the three primary goals. A summary of each roundtable follows:

Goal 1 Roundtable: Enable Digital Capabilities at SMMs

A vast majority of U.S. manufacturers are SMMs, representing approximately 300,000[1,2] manufacturers and another 300,000 manufacturing related businesses. A core group of about 25,000 companies represents most of the economic output from this segment. Roundtable participants noted SMMs have been slow to convert to digital operations, let alone adopt AI systems, yet they are not only vital, but they are also the largest segment of the manufacturing ecosystem (albeit distributed) with a large share of operational data and knowhow. Having data in digital forms and starting to adopt AI solutions using the current state of the art requires a level of expertise and financial resources SMMs do not have.

Options to reduce these barriers include tools for easy digitalization and networking of data, and the formation of a platform environment where data, tools, applications, solutions, and use cases can be shared, offering incentives for sharing data and applications, and creating small scale demonstrations that

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[1] Manufacturing Extension Partnership (MEP) at the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce, Gaithersburg, Maryland (Apr 2015 –Jan 2021)

[2] National Association of Manufacturers

quantify the value of digital operations. Participants noted that SMMs will naturally gravitate toward advanced technologies if they are ready-to-use (high Technology Readiness Levels – TRLs), affordable, and create value. While low cost, easily deployable solutions do not yet exist in manufacturing, analogous software solutions enabled the digital transformations of many other industries long ago. With development of the appropriate software tools, the successes in industries such as financial services and retail distribution could be examples of how to approach AI adoption at SMMs.

Enabling initial digitalization in the core group of SMMs was considered a prerequisite to AI adoption and achievement of a resilient supply chain. For SMMs to develop digital capabilities, and resilient supply chains to manifest, simple, low cost, easy to use solutions, and tangible demonstrations of value are essential to accelerate AI adoption.

Goal 2 Roundtable: Incentivize AI Adoption Throughout Established Supply Chains

This discussion focused on approaches to incentivize AI adoption throughout established supply chains with an emphasis on building trust, sharing value, and overcoming resource differences. Participants described the flow of information, including data sharing among supply chain partners, and propagating defined applications from large companies down the supply chain to SMMs, a process which is usually managed by contractual agreements. However, there are numerous business and technical challenges in the process that make sharing information and data inefficient, especially when applied in advanced digital systems. Participants discussed these challenges and approaches to address them.

1. Many SMMs are not using digital sensors in their operations and do not have the resources to respond to the requirements of large companies. Development of small-scale demonstrations that highlight the value of digital systems could be used to stimulate SMMs interest in digital operations and AI systems. Community colleges were identified as regional locations for these demonstrations.
2. The data generated by machines and process operations is highly variable and difficult to use in AI applications. Standards for data and data formats would make information processing more efficient and support development of customized applications and analytics. Large corporations were identified as leaders that could support agreement on formats and the use of often existing standards throughout a supply chain. Machine and equipment builders could implement formats and standards to ensure compatibility of data streams for machine learning, at least for identical machine models.
3. Of the machines and process equipment currently in operation in the U.S., most in use, especially by SMMs, do not have digital capability. The development and distribution of "black boxes," i.e., ready-to-go, hardware units for connecting wired and wireless sensors and for ingesting and transmitting data, was discussed as an important way to enable digital capability on legacy machines.
4. The "cost share" and the associated administrative requirements in various government programs and manufacturing institutes was cited in the roundtable as a barrier to participation by SMMs with limited resources.

Goal 3 Roundtable: Enable New Business Models for AI Adoption

This roundtable explored strategies to enable new AI business models in the manufacturing industry. A standard and secure way to selectively share or provide data in useful forms was viewed as essential to convince manufacturers to use digital methods both inside and outside their organizations. Other important topics included expanded business models using digital methods to provide AI educational opportunities, and the need for a national repository for critical manufacturing data especially test results. In summary, the participants agreed on the following needs to enable these new business models:

1. Organizations that can provide AI expertise, support, infrastructure, and a repository for manufacturing data and publishing use cases to SMMs.
2. A set of tools for privacy preserving encryption, categorizing, integrating, uploading, and making data available for generating AI/ML solutions.
3. A Platform with a subscription-based model where resources and data can be shared, exchanged, or purchased, and solutions provided for a fee. The Platform should also include search engines for finding capabilities and matchmaking between problems and experts.

Workshop 3 Actionable Roadmap and Recommendations

The objective for Workshop 3 was development of an actionable roadmap to accelerate digitalization and the adoption of AI in U.S. manufacturing, and promote global leadership in productivity, quality, resiliency, and environmental sustainability. During the roundtables, four common themes emerged from all the discussions:

- Improved digital capability at SMMs was identified as a prerequisite for industry-wide adoption of AI.
- Structural business and technological limitations are inhibiting AI adoption.
- Broad adoption of AI will require widespread, technician-friendly access to sophisticated software tools that are broadly applicable and provided on a software-as-a-service basis at a modest cost.
- Technologies required for robust, scaled, unbiased, and trustworthy AI in manufacturing are largely at a nascent stage and require continued R&D investment.

In reading **Figure 1** from left to right, the first column is focused on addressing industry constraints. Somewhat predictably, most roundtable discussions involved descriptions of these constraints, and participants suggested taking actions to address them with a particular focus on SMMs, R&D, and scalability to stimulate a pathway to start building solutions. There was a strong theme that a focus on SMMs would result in the easy-to-use tools, infrastructure, and training that large companies can also use to great benefit.

The roundtables provided focus and substance around the actions to address seven structural constraints that are impeding AI adoption in manufacturing and need to be overcome to start. Although addressing these is likely to produce incremental progress in the beginning, the knowledge and benefits from successful AI adoptions can be used to reshape programs and accelerate the application of AI technologies in manufacturing operations. Also, addressing these as an integrated set refers to reaching sufficient industry agreement across all of them at acceptable rudimentary levels to demonstrate an overall capability that does not currently exist. The seven structural constraints and actions to address them are as follows:

1) **Agree on preliminary standardized data formats**
    - Define and reach agreement on standardized data formats (metadata) to get started on some demonstrations of problems, as well as a repository to store data, especially for test results. These agreements should demonstrate how multiple companies in the manufacturing industry could benefit by facilitating the capability of machines to execute machine learning solutions and developing customized apps for specific segments and applications.
2) **Create a business platform**
    - Develop and implement a managed and searchable business marketplace platform where companies can upload and download software tools, models, education programs, and benchmark data sets and results, success stories, and other information.
3) **Financial incentives for digital upgrades**
    - Provide financial incentives with reduced administrative requirements for SMMs to buy digital capable equipment, software tools, etc. For example, if government funds were available, qualified SMMs could apply for funding to acquire the hardware and software required to digitize their operation. An exchange platform could operate as a trusted source of information for SMMs to identify appropriate hardware and software.
4) **Build educational programs**
    - Provide funding for digital training at SMMs.
    - Fund AI, data acquisition, and digital literacy educational programs at universities and colleges, especially community colleges.
    - Document the results of these activities, especially solutions to specific problems, for publication on the business platform.
5) **Show value with use cases and blueprints for solutions**
    - Develop multiple operational, re-usable cases for specific applications and industry segments to demonstrate the value of AI and the value of reusable blueprints. For example, use case demonstrations might be available in the aerospace industry, automotive industry, Department of Defense (DOD), and Manufacturing USA institutes.
    - For SMMs, the use cases should demonstrate value at a scale consistent with their capabilities and be mobile to allow regional operation and encourage participation. Essentially carry a "live" demonstration to an SMMs' home base.
    - Large organizations with significant digital capabilities could develop blueprint solutions to complex use case challenges and openly share the results in the business platform. Examples of complex use cases include intercompany data transfer and analysis (i.e., data exchange for interoperability), coordination across a supply chain, or a solution set involving the interaction of several of the key structural constraints identified in Workshop 3.
6) **Data enable legacy equipment**
    - Develop cost effective Internet of Things (IoT) edge devices that can data-enable legacy manufacturing equipment that still has useful life, especially for SMMs. Some existing examples of this approach were discussed in the roundtables.
7) **Encourage use of in-kind contributions as "cost share"**
    - Existing cost share requirements in government programs, competitive funding solicitations, and membership in manufacturing institutes can be a major barrier to participation, especially for SMMs with limited resources and experience with digital operations. Cost share requirements

should be revised to prioritize in-kind contributions, particularly for data. For example, convert a financial requirement for participation in a program or an institute to a data sharing requirement.

Figure 2: Interrelated Structural Constraints Inhibiting AI Adoption

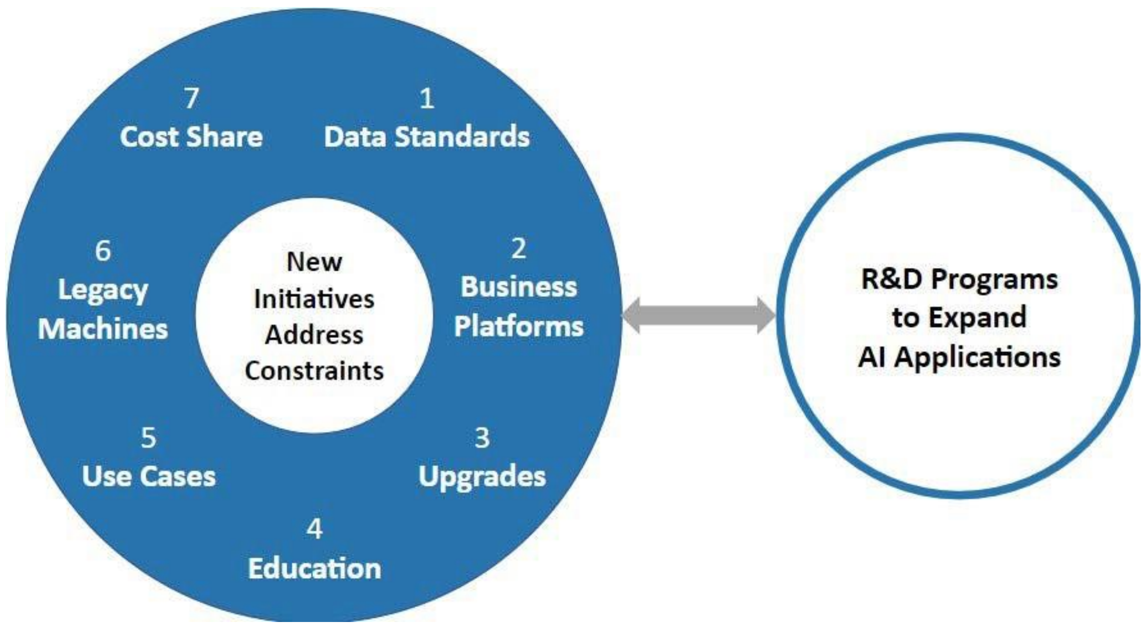


Figure 2 is a graphic display showing the seven structural constraints linked together in a ring. The ring represents the continuous linkage among all the constraints and the need for interrelated solutions. Developing new prerequisite programs to address the constraints will require action across multiple constraints, industry consensus, coordination with existing programs, and innovations in R&D. Beyond incremental progress, the roadmap for AI adoption involves significant R&D challenges that can influence and shape all roadmap activities. The full potential of AI will require continued R&D and development of innovative services for manufacturers of all sizes, including unique approaches to market-driven agreements for industry collaborations. Four categories of cross roadmap R&D were also summarized in Workshop 3:

1. **AI methods, tools, and data aggregation for manufacturing's time-centered data types**: While existing AI and data analytics technologies in the industry are sufficient to provide value in limited applications, considerable R&D work is required to develop more robust AI methods, tools, and data collection protocols that are suited for the time-sensitive data relevant to manufacturing. Those methods are likely to require cutting edge research since they will differ substantially from established deep learning methods, which were generally developed to perform well in applications involving image recognition.
2. **Data to automate algorithm building and continuous tuning:** The fundamental advantage of AI technologies is learning from data. However, the infrastructure does not exist to aggregate data from multiple operations and manufactures, provide access to proven data, build algorithms, and

continuously update data and the algorithms as additional information becomes available. Significant R&D is required to develop this infrastructure and set the stage for the long-term achievement of wide access to machine learning solutions tailored to specific industrial applications that can execute locally, and fine-tune with continued acquisition of local data.

3. **Going beyond incremental change:** The roles of networks and industry interconnectedness in manufacturing operations are largely untested. The network approach tends to be outside the prevailing appetites of large companies that favor incremental, top-down solutions. R&D is needed to develop low cost, easily accessible network tools that can be widely distributed on the web (i.e., data-as-services or manufacturing-as-services) allowing SMMs to create immediate value and drive AI adoption from the bottom up. The tools required for aggregating data and building algorithms at scale in a networked environment are significantly different than top-down centralized approaches.
4. **Scaling data and operational interoperability:** Products-as-services is a new business model with traction in large companies that produce end-use products. In these companies, in-service product data is used to sell services to buyers that support the product, and the manufacturer can use data to improve the product, which creates a continuous cycle of improvements. By recognizing that every supplier is a manufacturer, and every manufacturer is a supplier, this concept can be extended to entire supply chains and facilitate interoperability and resiliency. The R&D challenge is to develop tools and business models that enable suppliers and manufacturers to access measurements and exchange data to act together to improve operations up and down the supply chain.

Executing the Roadmap: Formulating National Program Strategies

The seven structural constraints defined in the Workshop 3 roundtables are impacting all aspects of AI adoption across all sectors of the manufacturing industry and impeding the start of a cycle of industry adoption. As a result, individual companies or supply chains are not suited to implement industry-wide programs to address them. Roundtable participants shared the view that targeted government actions are required to address these interrelated problems, and to coordinate the interaction of existing AI programs with new initiatives to start the adoption cycle identified in the roadmap. An examination of the seven integrated actions shows that these enable an entrée into each of the primary goals driving the roadmap. The four R&D areas start with the current state of the industry and how to use current technologies, but are defined to look forward to all areas of monetization.

Although the immediate actions required to address these constraints will initially produce incremental progress in the use of AI, participants agreed that incremental improvements with these directional changes could stimulate a pathway toward broad AI adoption. Increased use of AI can lead to the availability of open data sets which are a prerequisite for the R&D programs needed to innovate advanced AI methods and associated tools. As more powerful software tools become accessible to industry, they will drive the value that powers the propagation of new business models that employ the tools. Some of the new business models will be implemented by existing companies, but many will be implemented by new entrants who see profit potential and have the risk appetite and expertise to enter the market. This is the likely path to the emergence of AI-fueled data aggregation and a solutions infrastructure for manufacturing.

The roadmap is premised on Public Private Partnerships (PPPs) to coordinate the preparation of the U.S. manufacturing industry for an AI-enabled future, and foster the fundamental research needed to make that future possible. The federal government has successfully created this type of organization in the past and many existing programs can serve as component elements or models for component elements. An opportunity exists to build on past PPPs successes and adapt them to fit the requirements for AI adoption in U.S. manufacturing companies. Additional reference activities that could inform or provide direct support include:

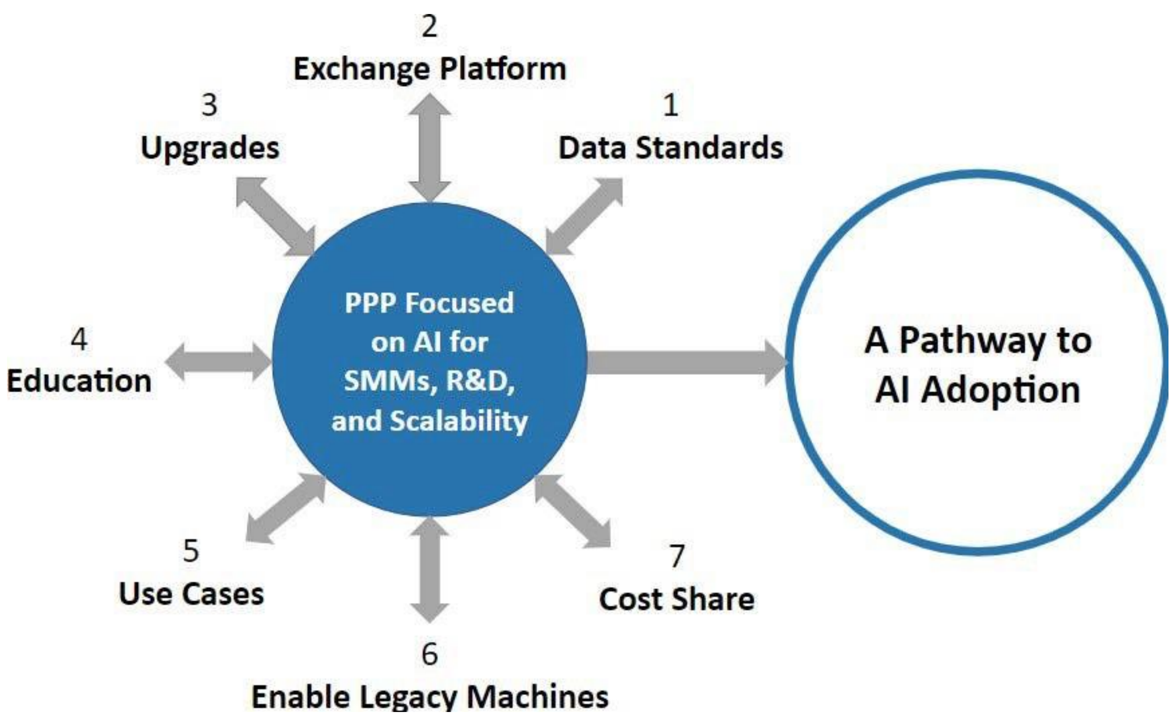
- In the financial accounting industry, the Financial Accounting Foundation (FAF), an independent, private sector, not-for-profit organization, operates for the purpose of supporting efficient, robust capital markets. The FAF administers the Generally Accepted Accounting Principles (GAAP) standards and its use by companies, not-for-profits, governments, and other organizations to prepare their financial statements.
- The Manufacturing USA Institutes are models of successful PPPs that already include some elements of AI business and operational infrastructure and application technologies. Notably, CESMII, MxD, and CyManII are three PPPs focused specifically on manufacturing digitalization.
- Most recently, the National Cybersecurity Center of Excellence (NCCoE) was formed as part of the National Institute of Standards and Technology (NIST). NCCoE brings together experts from industry, government, and academia to address the real-world needs of securing complex IT systems and protecting the nation's critical infrastructure. NCCoE publishes example solutions that provide organizations the details needed to recreate the solution in part or in full.
- The National Science Foundation's (NSF) National Artificial Intelligence Research Institutes bring together collaborators from universities, industry, and government agencies to perform foundational AI research that goes beyond applying known techniques to discover new methods with new applications. This creates a virtuous cycle where foundational results are applied, and applications can be generalized and made foundational.

Figure 3 is a graphic representation of how the PPPs could be structured, with an overall goal to accelerate innovation and the rate of AI adoption. These PPPs organizations would need to be chartered to pursue a collaborative process with industry that defines a scope of work to solve pressing AI challenges, assemble teams from industry, government, and academia to address all aspects of the challenge, and build practical, repeatable, reusable demonstrations of solutions. Rather than attempting to create a broad, unified solution to all seven structural constraints, or conduct deep R&D on individual constraints, the PPPs need to address the technical and business challenges of integrated solutions associated with specific use cases in real-world AI applications in manufacturing. To accomplish this mission, the PPPs could focus on the following activities:

- Organize and fund industry demonstrations of the interaction of the seven structural constraints to define points of entry for initial AI adoption in the roadmap
- Fund targeted technical and business R&D and publish solutions
- Bring industry, government, and academic resources together, including manufacturing experts and AI experts
- Identify problems and develop solutions
- Coordinate with multi-agency programs
- Document and promote adoption of solutions
- Educate the workforce at all corporate levels

- Provide and manage a repository for exchange of information
- Support adoption of new business models

Figure 3: PPPs Focused on SMMs, R&D, and Scalability to Accelerate AI Adoption



Concluding Statement

The roadmap presented in this report is a compilation of inputs from all three workshops in the Symposium. It recognizes that industry awareness of AI and digitalization is growing, and that U.S. manufacturing companies are genuinely interested in adopting AI technology. Many large corporations and a few SMMs are currently working to incorporate AI technology into their operations, but the pace of adoption is limited by the slow pace of digital transformation in the U.S. manufacturing industry. At present, most successful use cases for AI in manufacturing are heroic efforts that require advanced education and training and do not scale to other equipment, facilities, or companies. Because of the seven structural constraints, the gap in capability between large and small companies for AI implementations continues to widen, slowing impact and exacerbating challenges. It has already proven difficult to overcome these structural constraints through incremental improvements on individual shop floors. Broad, overarching programs with a systematic view of the power of AI methods to provide industry-wide benefits through network effects are needed to stimulate, accelerate, and scale the adoption process. The U.S. is the world leader in most of the industry sectors that have adopted that approach and no country has better capabilities to bring a similar transformation to manufacturing.

The Symposium recommendations also include a roadmap execution strategy that starts with a program that demonstrates that diverse manufacturing challenges can be addressed with an integrated set of 'first pass' actions on seven constraints to demonstrate how business collaborations can succeed and produce value. A successful ‘first pass’ industry collaboration demonstrates value and how an industry wide AI adoption can proceed. Given the multi-disciplinary and multi-stakeholder collaboration among industry, academia, and government that is needed to start, nurture and grow industry-wide strategies, Public Private Partnerships (PPPs), for which there are many successful models, are the most appropriate coordinating structures. An opportunity exists to build on past PPPs successes and adapt them to fit the requirements for AI adoption in U.S. manufacturing companies. However, the actions being recommended in this report will require expansive PPPs to pursue the collaborative processes required to define programs that identify pressing AI challenges and the teams from industry, government, and academia to address them. The PPPs must be structured to facilitate practical, repeatable demonstrations of solutions, and focus on solutions involving a wide range of tools and products that address scalability. Rather than attempting to create a broad, unified solution to all seven structural constraints, or conduct deep R&D on individual constraints, the PPPs need to address the technical and business challenges of multiple approaches to integrated solutions associated with specific use cases in real world AI applications in manufacturing.

Additionally, PPPs collaborations of industry, government, and academia are needed to provide industry-wide coordination through a governance and execution structure that involves all stakeholders in defining programs and funding requirements, supports the implementation of programs and distribution of funds, and coordinates initiatives. The successes demonstrated by the actions of PPPs will reduce the risk of applying AI technologies in manufacturing operations, making it easier for entrepreneurs and private investors to visualize innovative operational products and business models. As this process takes hold, the U.S. manufacturing industry will be on its way to achieving global competitiveness and resilient supply chains.

Appendix

Workshop 3 Participation

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*Through Workshop 2