Symposium: Strategy for Resilient Manufacturing Ecosystems Through Artificial Intelligence

Report from the First Symposium Workshop

Aligning Artificial Intelligence and U.S. Advanced Manufacturing Competitiveness

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Executive Summary

Artificial Intelligence (AI) refers to a rich spectrum of data and knowledge driven technologies that have collectively taken on a "silver bullet" status in many countries, including the United States. A global competition is underway to achieve economic leadership through the development and application of AI technologies in key industries, often supported by large government investments.

The U.S. priorities for federal investment in AI R&D are summarized in several reports from government agencies. These reports highlight the strategic importance of AI in advanced manufacturing, but they do not present a broad, actionable strategy for applying AI in the manufacturing industry.

In building on these previous reports, the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST) have sponsored a symposium titled the "Strategy for Resilient Manufacturing Ecosystems Through Artificial Intelligence." The symposium will define opportunities for leveraging AI in the U.S. advanced manufacturing sector and has been organized into a series of three workshops. The first workshop (Workshop 1), "Aligning Artificial Intelligence and U.S. Advanced Manufacturing Competitiveness," was held on December 2 and 4, 2020. This workshop was unique in bringing together experts in advanced manufacturing, AI, IT, and computer science from industry, universities, federal agencies, and national laboratories.

Workshop participants were enthusiastic about both the near term and long term benefits of applying AI to manufacturing. These included far better use of industry data and scaled use of domain knowlege throughout the industry, noting that AI is not a replacement for domain knowledge. They identified priority opportunities, challenges, and collaboration points for accelerating the implementation of AI in manufacturing, and used the span of economic value as the topmost driver – market share, productivity, energy and material consumption, national security, and climate, environmental, and ecosystem impacts. A key observation was that manufacturing has derived little benefit from the *network effects* that have transformed other industries, even though the potential is high for *AI, machine learning, predictive modeling, and networked data centric analytics* and solutions to enable such a transformation.

In assessing AI in manufacturing, it was noted that current AI applications are almost *exclusively* for machine and operational units, i.e., component levels within individual company operations, and rarely extend to line operations, intracompany systems, or intercompany supply chains. This fact focused workshop discussions on the transformational opportunities afforded by the application of AI methods and tools to support manufacturing operations beyond the component level. The participants stressed that, with broad industry adoption, AI and machine learning systems have the potential to transform the prevailing manufacturing business model, which emphasizes the proprietary nature of data. This transformation, which is essential for the successful implementation of AI solutions, can also be enabled

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.

Networking creates digital connections among devices, machines, equipment, databases, computer programs, and users, to provide the **connectedness** needed to exchange information, make decisions, and take actions.

Predictive Modeling is the use of data, AI, machine learning, simulation, and digital twins to assess, predict, and anticipate process, product, and operational behaviors for control, design, optimization, health, and failure prevention and mitigation.

Network Effects produce increased benefits for network users as the number of connected user nodes increases by expanding the availability of information and knowledge accessible to all.

by AI tools for data privacy, discovery, and reuse, essentially using AI to enable AI. The workshop identified seven key principles for realizing full value and wide adoption of AI in manufacturing:

1) The entire manufacturing industry, including small, medium, and large manufacturers, suppliers, and R&D collaborators, must approach digital transformation at the industry level. There are significant benefits to adopting highly connected industry business practices that involve shared data and knowhow, in addition to scaling the customary contractual exchange of data.
2) AI must focus on untapped opportunities within and across all operations, but within the span of economic benefit. Access to routine industry data and the right tools for putting these data to use for economic benefit is the key requirement for wide industry adoption of AI.
3) There is a need for appropriate methods and tools to provide assurances that critical proprietary data will be protected, while allowing noncritical data to be shared for the training of AI systems. Such tools must provide the guarantees on security and control for data access that manufacturing companies require for the full benefit of network effects to be realized on a national scale.
4) Agreements and de facto standards for data formats, timing, and sharing will be needed, along with the implementation tools needed to apply them to produce value.
5) Important lessons for building industry-wide data and cross-industry modeling networks critical for AI can be learned from other industries that have gained competitive advantages by doing so.
6) AI tools that link supply chains can improve manufacturing resilience by increasing supply chain visibility and coordination, decreasing duplication of productive capacity, improving productivity management across companies, and providing individual manufacturers with the flexibility to re-tool and re-specify operations to change product type and production volume.
7) AI tools and networked, data centric modeling approaches are actively researched and rapidly evolving, making it difficult to predict the skills that tomorrow's manufacturing workforce will need, but we cannot wait for tomorrow's tools to be available. There is an urgent need to configure educational programs that provide the foundational knowledge that today's engineers and technicians will need, using existing data centric methods as a bridge to the AI tools of the future.

Workshop 1 identified four primary areas of joint AI and manufacturing R&D that provide an industry-wide framework for development and implementation. Importantly, the framework was designed to provide benefits both to individual manufacturers and industry-wide by creating a virtuous cycle of expanding capability and adoption. The four areas are:

- AI for Industry-Wide Data Sharing
- AI for the Factory Floor
- AI for Discovery of Capabilities and Solutions
- AI for Building Resilient Supply Chains

The seven principles, the AI opportunity areas, and the implementation framework identified in Workshop 1 provide the basis for Workshop 2, which will address how to bring AI and manufacturing communities together to create, develop, and implement new tools to enable a cycle of research, development, and adoption. Critical issues that will be addressed in Workshop 2 are the foundational requirements for interconnectedness, including the ability to manage, exchange, and share data with trust; the availability of shareable data for building new AI tools and applications; and the ability to access and reuse data and application capabilities and knowhow throughout the industry. These broad-based tools can enable new foundational tools to address hoped-for advances in manufacturing productivity, precision, and performance, particularly by providing increased capabilities to assess and predict at affordable cost. The expected overall impact will be to enable AI solutions for search, discovery, and reuse at scale. Workshop 3 will produce a roadmap for advancing AI to increase the resilience and competitiveness of advanced manufacturing.

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Introduction

Manufacturing is important to global competitiveness because it impacts jobs, national security, energy and material consumption, climate change, environmental sustainability, and societal health and safety. Because advanced manufacturing operations depend on experience and knowhow, in addition to codified technical and scientific knowledge, the potential for using AI to enhance production by accessing the implicit knowledge incorporated in the industry's extensive and rich data sources is high.

The U.S. priorities for federal investment in AI R&D are summarized in the *National AI Research and Development (R&D) Strategic Plan, 2019 Update*,[1] which calls out manufacturing as one of several sectors that can be transformed by AI. The *Strategy for American Leadership in Advanced Manufacturing*[2] specifically highlights the importance of AI implementation as a priority R&D area. *Recommendations for Strengthening American Leadership in Industries of the Future*[3] proposes the establishment of an Industry of the Future (IotF) Institute on Generative Design in Advanced Manufacturing to coordinate the R&D required to advance AI and machine learning tools. These reports all emphasize the strategic importance of AI in advanced manufacturing.

Given the complexity of the issues, the characteristics of the manufacturing industry, and the broadly scoped definition and spectrum of AI possibilities, a comprehensive symposium comprised of a series of three workshops has been planned to examine manufacturing competitiveness and produce a strategy for realizing resilient manufacturing ecosystems through AI. The progression of workshops has been planned to reflect a logical flow of discussion that results in an implementation roadmap:

1) Workshop 1, to identify priority opportunities and key challenges;
2) Workshop 2, to address the R&D and establish an implementation framework for applying AI to address the opportunities and challenges identified in Workshop 1; and
3) Workshop 3, to produce a roadmap for advancing the use of AI in manufacturing and provide recommendations for its implementation.

Workshop 1 benefitted from the opinions and experience of experts in manufacturing and AI from academia, industry, and government and was unique in bringing together communities that have not extensively interacted previously. The participants in the workshop sessions included: (1) industrial leaders in manufacturing operations and manufacturing information technology (IT), (2) researchers in schools of engineering, business, and computer science, (3) commercial manufacturing IT and AI service providers, and (4) technical program personnel from across the federal agencies and laboratories. Appendices A through D provide details on the workshop and the symposium organization, leadership, and participants.

Industry-wide Strategies

The diversity of experience and organizations represented in the workshop resulted in lively discussions about the breadth of opportunities for the near and long term adoption of AI technology in manufacturing. The current strategy for implementation can be characterized as largely "bottoms up," a reference to focusing on the high cost development of applications in individual factories, mostly for machine and

[1] https://www.nitrd.gov/pubs/National-AI-RD-Strategy-2019.pdf

[2] https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/10/Advanced-Manufacturing-Strategic-Plan-2018.pdf

[3] https://science.osti.gov/-/media/_/pdf/about/pcast/202006/PCAST_June_2020_Report.pdf?la=en&hash=019A4F17C79FDEE5005C51D3D6CAC81FB31E3ABC

operational units producing high-value products. This bottoms-up strategy implicitly assumes that industry data collaboration will occur, and market forces will drive needed investment in development of new infrastructure, technology, and supply chain collaboration, including small, medium, and large manufacturers. This view of factory floor applications through the lens of existing practice fails to consider the largely unrealized potential of industry-wide strategies that require collaboration, new standards, and methods for securely exchanging data.

There was also a strong collective sense that manufacturing presents a promising problem space with abundant opportunities for collaboration for the AI community. The dimensions of this disciplinary opportunity encompassed the need to enable individual manufacturers to identify and safely provide access to non-proprietary data, information, and capability, and the ability to locate, access, and use relevant resources for a particular manufacturing problem. These capabilities would allow individual manufacturers to be informed by the extensive body of non-proprietary manufacturing knowledge accumulated industry-wide through experience and scientific investigation, rather than relying primarily on their own limited experience.

More specifically, the potential for sourcing and using operational data and domain knowhow in industry-wide strategies emerged from the cross community perspective of the workshop. It was emphasized that proprietary, product specific data must be maintained secret, but that most data from widely used machines, processes and operations could be shared to provide generalized solutions that improve industry-wide productivity. While other industries have gained competitive advantages by exploiting the network effects that interconnectedness generates around common needs, manufacturing companies linger in established business models emphasizing the acquisition of assets, control of curated supply chains, and business to business transactional or contractual relationships. These are linear business relationships that sacrifice the potential for exponential scaling that interconnected businesses enjoy.

Today's access to data management and computational capabilities simply did not exist a decade ago and an unprecedented capacity to collect and manage massive amounts of data is now commonplace with network based cloud services. Breakthrough IT infrastructure, data science, and other methods now exist to apply data analytics, machine learning, digital twins, and other predictive, reactive and discovery modeling approaches to amazingly large data sets that can encompass cross-industry modeling. Networked industry-wide modeling and the exploitation of network effects are not new concepts; many other industries have already been transformed by the competitive advantages they provide. Manufacturing has different constraints and risks than other industries, but there is no compelling reason that the manufacturing industry could not derive increased benefit from these advances.

While the interest in industry-wide strategies was high, there was, at the same time, the practical consideration that digital innovations to unleash the potential of AI must align with the ongoing digital transformation of manufacturing operations, making it essential that AI innovations result in increased profitability to incentivize manufacturers to adopt them. Any associated product quality and operational performance improvements provide significant benefits to manufacturers, but only to the extent that they increase sales due to product and service differentiation, increase productivity, and/or reduce costs due to reductions in time, waste, and defective product. Profitability is the overriding driver. While a growing number of demonstrations of the use of AI in manufacturing can be identified in large, well-financed companies, individual, independently developed solutions are typically expensive, do not generalize easily, and have proven difficult to scale. Therefore, it is likely that the widespread adoption of AI in manufacturing will be paced by the availability of AI solutions that can be implemented at reasonable cost and by a manufacturing workforce that mostly lacks specialized AI expertise. This concept of needing scaled access to cost effective solutions and a skilled workforce to implement solutions for cost improvement is also not new. What is new is the potential for AI to be a strategic enabler of industry-wide approaches that benefit individual manufacturers. Because companies will use profitability as a key metric, broad industry adoption, from factories to supply chains, will be driven by cost, with the cost of acquiring a workforce that can implement the tools an important factor.

It is important to note that the benefits derived from industry-wide actions can enable vastly increased opportunities for the small and medium size businesses that constitute about 98% of all U.S. manufacturers. In this regard, it is likely that different innovations initially will provide benefits to different segments of the industry and sizes of companies. Just as the early adopters of web-based commerce were small businesses that tolerated quirky software to gain market access, new AI tools may allow small manufacturers to acquire new customers outside established supply chains and small companies to source manufacturing services domestically.

The consideration of industry-wide AI strategies also stimulated significant discussion on cultural and educational barriers to AI adoption. In manufacturing, legacy practices, cultures, real and perceived risks, and a lack of transparency and trust are challenges to expanding the role of AI that are at least as great as the technical challenges. Discussions centered on the potential for homomorphic encryption, federated learning, and synthetic data methods to provide access to data needed for machine learning without revealing sensitive trade secrets or production status information. These methods are active areas of AI research that should be expanded to include manufacturing relevant applications. Business sensitive data i.e proprietary data, needs to be identified and separated from data about commonly used machines, operations, processes, and materials that can be safely and securely shared only with the intended recipient. Finally, there is a need for applications and associated industry datasets to be identified and prioritized and to make the relevant data from these available to university researchers who can more robustly research and develop new AI, machine learning, predictive, and networked modeling methods. It is instructive to draw an analogy with the annual ImageNet competition, which made several million labeled images publicly available to researchers. A competitor in the 2012 edition featured the advent of deep learning, which smashed every previous record for image identification and ushered in the age of commercial machine learning.

Finally, and importantly, implementation of AI in manufacturing requires a dramatically expanded and technologically capable advanced manufacturing workforce, but AI tools are rapidly evolving, making it difficult to predict the skills that tomorrow's manufacturing workforce will need. History has shown that it is impossible for workforce training to drive technology adoption. Rather, benefits to individual companies will drive workforce needs as companies adopting AI technologies accrue accelerating advantages. It is in this context of technology adoption that the workforce is tied to an industry-wide strategy. Just as a shortage of HTML programmers did not prove to be an impediment to the explosive growth of the Internet and web based commerce, an AI based economy is expected to grow and accelerate with the development of accessible tools and methods that enable the application of AI by non-specialists at dramatically reduced costs.

AI for Industry-Wide Data Sharing

The manufacturing sector generates more measured, observational, operational, modeled and experience-based data than any other sector of the economy, even surpassing the financial sector. These data offer an industry base that could be contextualized and made available to enable radical innovations by AI in business practices, process engineering, product and system design, scalability, and sustainability, going far beyond improving the efficiency of manufacturing methods at individual sites. On the other hand, few companies generate enough of the right data internally to apply AI, even for narrowly focused applications on process or machine units. This contrast of a data rich industry with data poor individual manufacturers drove the conclusion that the entire manufacturing industry can benefit from innovative AI tools and methods that aggregate data across manufacturers, while protecting critical intellectual property and preserving data privacy and provenance. Since the capabilities of and confidence in the anticipated data infrastructure can be expected to increase with additional users and contributors, the benefits of participation are expected to increase with time, fulfilling the fundamental requirement for a viable, self-sustaining, and self-financing network. In a virtuous cycle, the contributions of individual manufacturers enable broad, new industry-wide capabilities that provide productivity benefits to the contributing companies. Furthermore, the accompanying opportunities for researching new methods should provide opportunities for founding new businesses to deliver solutions to manufacturers.

A major discussion point concerned the tight grip manufacturing companies maintain on intellectual property, often extended to all production relevant data and information. This culture of secrecy emerged from a craft culture that placed high value on expertise and is as old as the industry itself. It has caused few problems to date because the culture is pervasive worldwide, and until now there has been little or no opportunity for firms to benefit financially from sharing manufacturing data. However, as indicated in this report, AI has the potential to radically increase the value of manufacturing operational and product data by harvesting the implicit knowledge incorporated in it and harnessing its predictive, reactive and discovery capacity, again through data centric modeling, machine learning, simulations, and digital twins. Since the value of this implicit knowledge almost certainly exceeds the value of explicit manufacturing knowledge, this information must be made accessible to unlock its value.

Workshop participants highlighted some specific observations related to shareable, trusted data:

- There is potential for federated learning, homomorphic encryption, and synthetic data methods to provide assurance of data protection. These methods are under active investigation by the AI community, but there is little investigation in the manufacturing domain. Fair and consistent methods are also needed for the valuation of data. Methods for ensuring data integrity, security and privacy are critical.
- Some suggested the need for repositories of curated and labeled data, and others observed the potential for self-curation by grouping production data across companies by machine model number, since each machine model is typically produced in large numbers. Participants also cited web-based, vendor-provided machine tool thermal error compensation services as an emerging model for providing services with secure data sharing.
- The IT industry has pioneered best practices that can be adopted by the manufacturing sector to begin taking advantage of the benefits of shared data, while still retaining a company’s competitive advantage.
- Participants noted the burden of data cleaning and conditioning, lamenting the fact that highly trained data scientists must be pressed into service as “data janitors.” What is particularly important is the ability to identify, assemble and curate data that is relevant to solving an particular problem while enabling the reuse of that data in addressing related problems. Such generalization and reuse of non-proprietary data allows the applications to scale.
- In addressing the critical interactions of humans with manufacturing equipment and systems, the workshop participants looked for direction from AI applications in intelligent, autonomous robotics. These efforts include automation of tasks that require humanlike manipulation, robots with greater autonomy and flexibility, and integration of humans and machines to perform tasks.
- Participants stressed the need to determine and tune the level of decision making authority an AI system has to each use case.

AI for the Factory Floor

The benefits of employing real time sensing with modeling, in particular predictive modeling, to control production quality in-process have been recognized almost since the advent of digital computation. This concept lies at the core of Industry 4.0, Smart Manufacturing, Digital Manufacturing, etc. and is fulfilled in the notion of a digital twin (recognizing that definitions of digital twin vary widely). Over the past half century of computational modeling, manufacturing science has progressed to the point where almost any manufacturing process can be brought under computer control but the solutions are expensive, time consuming, and often require the capabilities of highly trained professionals. Worse, they lack generality and often can be applied only to a limited range of processes or machines and are not easily maintained. This has limited the penetration of solutions to expensive, difficult to produce products, such as jet engines, or very high volume production as in semiconductors, automotive components, and materials in the process industries.

Computational modeling challenges for harnessing mountains of data from factory operations led to a focused discussion on machine learning methods and their potential to provide the generality and the associated dramatic cost savings that computational modeling methods have so far failed to achieve. This potential was reinforced by representatives from the Manufacturing USA Institutes who stressed the importance of data enabled AI solutions. Many of the Manufacturing USA Institutes already have a wide spectrum of AI and ML applications underway.

Workshop participants highlighted some specific observations related to modeling and production control:

- There was much discussion about merging AI and physicochemical modeling methods to reduce the amount of data needed to train machine learning systems. While highly desirable, such methods still need to address the high development cost and narrow application range of most physicochemical models.
- Data centric methods have a potential to reduce implementation time and cost, and increase generality, but they need to be explainable and carefully validated to be used with confidence. These methods must be investigated.
- Participants discussed the current success of applications that apply data analytics and statistical and parametric modeling. These data centric approaches are important precursors to the richer capabilities of AI and machine learning and can provide effective solutions today.
- AI for predictive maintenance and for quality assurance were offered as quick wins for every manufacturer to explore.
- AI and machine learning have the potential to provide the capability to automatically locate, configure, and install the data driven process control approaches that are appropriate to particular setups.
- The need for data standards was highlighted. One participant reported acquiring two machine tools with identical model numbers, one domestically produced and the other produced abroad by the same company. However, the control code and sensor outputs on the two machines were incompatible. At a minimum, all machine tools with the same model number need compatible outputs.
- Participants discussed concepts of portable AI models and open source code/tools/data to bridge the development gap.

AI for Discovery of Capabilities and Solutions

Once data, information, and application knowhow have been made accessible, they must be made discoverable. In this regard, manufacturing can take inspiration from the world wide web, where information holders voluntarily post information for users, often in the hope of deriving income. A series of discussions focused on prior attempts to automate the digital translation of design data, as represented in a Computer Aided Design (CAD) file, to manufacturing instructions with acceptable guarantees on the successful execution of those instructions. The key reference was with generative manufacturing, the prevailing model. In essence, the generative method employs software that incorporates explicit knowledge about manufacturing processes and machine capabilities to generate a process plan, thereby making process selection and planning accessible to non-experts.

The most successful application of the generative method has been in automating the generation of cutting paths for computer controlled machine tools. Commercial software designed for this purpose is available and widely used today. However, in spite of the widespread use of such programs, a significant fraction of software generated cutting paths fails to execute successfully. This requires intervention by human experts, and those interventions represent a major portion of the engineering cost of producing many machined parts. Similar attempts to automate the generation of process plans for other manufacturing processes have been notably less successful, including attempts to organize expert manufacturing knowledge to make it accessible to non-experts.

AI has the potential to identify manufacturers who already have the equipment, process plans, and expertise needed to manufacture a needed part by searching for similar parts, materials, machines, or processes manufacturers have previously produced or used. Of necessity, manufacturers collectively hold a vast library of three dimensional, geometrical representations of the parts they have produced in standard CAD formats. Because each part has already been produced, its manufacturer has an associated process plan, tooling, and the other specialized expertise required to produce it. Like case-based reasoning and retrieval, if a CAD library of these parts were accessible, indexable, and searchable, it could serve as the basis for an open marketplace for manufacturing services that would be particularly useful for small- and medium-sized companies that are frequently driven to seek offshore manufacturing sources. A search-based marketplace does not require the customer to possess any process expertise or require the manufacturer to disclose any information to the customer except price and delivery, making it attractive to small- and medium-sized manufacturers with concerns about intellectual property.

A similar search function might also allow manufacturers to reuse the data and modeling configurations and setups for commonly used process operations or machines. In general, there are levels of detail in specifying configurations. Several levels of detail could be relatively open without affecting proprietary concerns, but as configuration information becomes more specific and proprietary, sharing would need to become a business transaction. The issue becomes one of recalibrating intellectual property. CESMII[4] has been tackling this kind of approach through a concept named "Profile" that acts within a standard based data infrastructure stack. What is missing is a way to make the distributed library or capability accessible, indexable, and searchable.

The evolution of a networked system for the discovery of manufacturing resources might evolve along similar lines to the evolution of software tools for searching, browsing, and webpage creation on the Internet. Web-based tools evolved explosively to more powerful versions in a few short years in the mid-1990s from Lycos to Google, Mosaic to Internet Explorer, and Front Page to Word under the driving force

[4] Clean Energy Smart Manufacturing Innovation Institute, one of sixteen Manufacturing USA Institutes

of accelerating web-based commerce. The potential exists for new software tools to promote a similar expansion of web-based commerce in manufacturing.

Workshop participants highlighted some specific observations related to the discovery of manufacturing data and modeling application resources:

- A manufacturing web could provide the framework for greater interconnectedness and increasing a network effect for application resources.
- At the operations level, machine learning methods gain power with more data. This provides the potential for creating a data marketplace in which solution providers can purchase and aggregate data from multiple firms and charge them for process control services. But this solution is only viable if the data providers feel confident that their data will be protected.

The points above are about the distribution of AI tools, application capability, and knowhow, but their successful adoption is fundamentally dependent on people. The economics of AI ultimately depend on a close coupling of AI and human centric operations. The roles of people encompass the development of the tools, the development and sustainment of applications, and execution of the solution implementations. Publicly, AI has been associated with job loss, but the reality is that there is significant opportunity in thinking systematically about people, process and technology, especially when scaled across the industry to change the actual work content of manufacturing jobs.

What is urgently needed are educational programs that provide the foundational knowledge and skills that today's engineers and technicians need to be able to use and contribute to the AI tools, capabilities, and solutions that are emerging. Workshop discussions generated some potential approaches to move forward:

- AI programs could be developed that evaluate manufacturing companies, identify priority training areas, and offer customized training. As new technologies are incorporated into more factories, the need for workforce training will become more urgent.
- There is a need to create new ways to generate educational and training content, distribute that content to potential operators, and certify the operators' content knowledge.
- Just-in-time training, cross training, and "snackable" content need to be developed, and distribution of the content could include the creation of workforce standards to highlight the "personas" of operators in their functional positions.
- Whatever the form and function of training content, the resulting instructional materials must be configured to ensure economies of scale.
- While new forms of content are being created, it is imperative to advance and harness the coming generations' fluency with information technology.

AI for Building Resilient Supply Chains

The supply chain disruptions created by the Covid-19 pandemic have elevated manufacturing resilience to a national imperative by demonstrating the impossibility of managing national scale supply disruptions through company specific supply chains without vastly increased information sharing and coordination. Current efforts in applying AI methods to supply chain management are almost exclusively implemented in the proprietary supply chains of individual companies.

The workshop participants associated manufacturing resilience with the ability to adjust, reconstruct, and link supply chains to provide better management of productivity at a national scale, across companies and industries. This further implies that each manufacturer has the flexibility to change product lines and/or adjust product specifications. AI tools can improve manufacturing resilience by increasing supply chain visibility and coordination, decreasing duplication of productive capacity, and improving productivity management across companies by linking supply chains at a national scale. AI tools also support individual manufacturers with the complementary capability and flexibility to re-tool machines and re-specify operations to provide greater flexibility in product lines and volumes. Supply chains and individual manufacturers will need to act in concert, requiring the day-to-day availability of appropriate data, data interconnectedness, and decision support for industry-wide operational management, with full understanding that supply chain data is among the most sensitive data that manufacturers hold.

As discussed in previous sections, AI can play a transformational role in allowing manufacturers to securely exchange supply chain data and experience in a business to business, operation to operation sense. In addition to their work on AI production applications, the Manufacturing USA Institutes have stressed the industry-wide role of data in manufacturing competitiveness. The Institutes have collectively advocated for a digital supply chain data infrastructure involving small, medium, and large enterprises. This is part of comprehensive proposal that includes the concept of a Manufacturing Guard, a network of subject matter experts on manufacturing and production, a national supply chain data exchange, a Technology Corps to build an agile manufacturing workforce, and a Resilient Manufacturing Advisory Council. Together these form a public-private advisory for the national orchestration of supply chains, a function especially important in times of disruption[5].

Principles for Adoption of AI in Manufacturing

As discussed previously, an important reference of Workshop 1 are the benefits that have been realized in other industries from a scaled, networked, and interconnected infrastructure. The workshop identified seven key principles (also listed in the Executive Summary) to spur the adoption of AI in manufacturing:

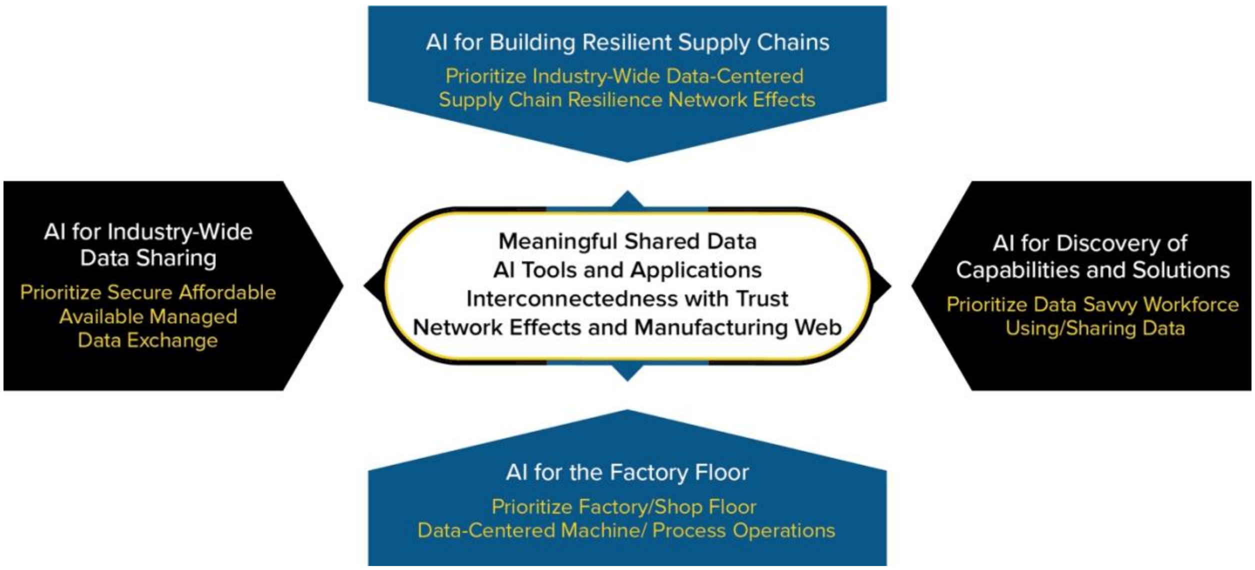
1) The entire manufacturing industry, including small, medium, and large manufacturers, suppliers, and R&D collaborators, must approach digital transformation at the industry level. There are significant benefits to adopting highly connected industry business practices that involve shared data and knowhow, in addition to scaling the customary contractual exchange of data.
2) AI must focus on untapped opportunities within and across all operations, but within the span of economic benefit. Access to routine industry data and the right tools for putting these data to use for economic benefit is the key requirement for wide industry adoption of AI.
3) There is a need for appropriate methods and tools to provide assurances that critical proprietary data will be protected, while allowing noncritical data to be shared for the training of AI systems. Such tools must provide the guarantees on security and control for data access that manufacturing companies require for the full benefit of network effects to be realized on a national scale.
4) Agreements and de facto standards for data formats, timing, and sharing will be needed, along with the implementation tools needed to apply them to produce value.
5) Important lessons for building industry-wide data and cross-industry modeling networks critical for AI can be learned from other industries that have gained competitive advantages by doing so.
6) AI tools that link supply chains can improve manufacturing resilience by increasing supply chain visibility and coordination, decreasing duplication of productive capacity, improving productivity management across companies, and providing individual manufacturers with the flexibility to re-tool and re-specify operations to change product type and production volume.
7) AI tools and networked, data centric modeling approaches are actively researched and rapidly evolving, making it difficult to predict the skills that tomorrow's manufacturing workforce will need, but we cannot wait for tomorrow's tools to be available. There is an urgent need to configure educational

[5] see https://www.mfgguard.com

programs that provide the foundational knowledge that today's engineers and technicians will need, using existing data centric methods as a bridge to the AI tools of the future.

A Framework to Stimulate Demand for Digitalization

The chart below groups the resonant workshop comments[6] in a graphic that came together as an implementation framework for driving demand for digitalization and the adoption of AI.



The blue regions at the top and bottom define the need to use industry-wide and factory specific AI strategies to link supply chains with the factory operations. This linkage is essential to providing benefits that directly impact operations on the factory floor, where the data needed to provide further benefits, is generated. Workshop participants, however, also identified high priority opportunities for AI at the supply chain level that included increasing yield, decreasing waste, preventing single source failure, providing supply chain as a service, shared inventory and capability data, and signals for real time supply and demand changes. Opportunities also included business to business interoperability, open source data for building AI tools, and machine/operations benchmark data. At the factory level, priority AI opportunities include augmenting human involvement, automated product testing and quality assurance, machine/operation monitoring and control, and providing higher quality information to human workers.

The black regions on the left and right address the need to establish industry-wide adoption of collaborative AI infrastructure and workforce strategies. As shown on the left, infrastructure, tools, and practices are needed to enable data sharing with trust. Workshop participants emphasized the need for data that is meaningful, available, accessible, affordable, reusable, sharable, secure, and trusted. The region on the right addresses the need for a workforce that can find and apply AI tools, data and modeling configurations and

[6] Resonant comments are those that arose in more than one source – workgroups, chat, email and panel notes

application knowhow in factory operations, and have the direction and capability to contribute data, information, and knowhow relative to a redefined value proposition for intellectual property.

The objective of the framework is to depict the key elements needed to secure the critical mass of industry commitment necessary for sustained use of AI and data centric solutions. A cycle of collaboration can start now using proven AI methods to produce tools for today's workforce and to define workforce training programs that can be updated with industry participation at a pace consistent with technology innovation and industry demand. This is also consistent with a general position taken by the workshop participants that the industry needs to start working with data now with a line of site to what is needed to enable AI in the future.

There are currently significant federal investments of an industry-wide nature. The Manufacturing Extension Program, the Manufacturing USA Institutes, and several federal agency and state programs are addressing pieces of an industry-wide approach through public-private partnerships. These efforts are directionally significant for data centric solutions, but they need augmentation and orchestration to be able to speed up adoption to address and scale AI for industry-wide impact. As overviewed in the body of this report, further research, development, and demonstration are needed on every aspect of the technology and educational supply chains. R&D on the specifics of a collaboration and business model for government, academic, and commercial business to work together would have a profound impact.

Next Steps

The workshop set the stage by explaining how AI can transform manufacturing competitiveness by enabling industry-wide collaboration, provided specific suggestions for opportunities to implement AI in advanced manufacturing, and framed perspectives that can inform the discussions in the future Workshops. The items enumerated below offer further context to be vetted with Workshop 1 participants and additional domain experts for framing the discussions in Workshop 2:

1) The broad proposition is to use AI methods to benefit manufacturing from factory level machine and process operations to supply chain operations by facilitating industry-wide strategies that overcome or circumvent industry-wide barriers.

2) One of the foundational truths about AI technology is that AI methods increase in power with increasing availability of the "right" data.

3) Workforce training cannot drive the need for AI adoption, rather competitiveness and industry benefit will drive workforce needs as AI technologies start to achieve industry-wide application.

4) It is essential to work within the current state of the manufacturing industry to find actions that incentivize companies to accelerate the pace of digitalization in an orchestrated manner for all four areas in the above chart together.

5) The key metrics in manufacturing companies are throughput, quality, on-time delivery, resilience, and cost; and cost is the overriding metric.

6) The AI adoption cycle must start with existing data analysis techniques, tools, and training that initially align with the ongoing digital transformation of manufacturing operations, which will provide the data for development of new AI tools and define workforce training needs.

7) Three technical foundations are required for interconnectedness and benefits of network effects:

    a. The ability to manage and share data with trust;

    b. The availability of shareable data for building new AI tools and applications; and
    c. The ability to access and reuse AI data and application capabilities throughout the industry.

8) There is a business need for distinguishing critical intellectual property from data that can be safely shared.

9) While a few companies are exploring the potential for search based methods to supplement and enhance generative methods in manufacturing, the subject requires more investigation and research.

10) Better coordination across many siloed efforts, especially with those that are publicly funded, could be a major accelerator for addressing national goals. Federal government incentives are essential for facilitating the formation of public/private partnerships to overcome collaboration barriers and encourage R&D in AI technologies and applications that support the full range of AI's interconnectedness potential.

In general, Workshop 1 set the stage for considering much broader roles for AI in achieving transformational manufacturing competitiveness than just factory level applications. Drawing from the experiences of other industries, the potential of industry connectedness and the resulting network effects is significant for manufacturing. These broader roles, however, were expressed in the context of the practical reality that the manufacturing industry does not have a history with or a culture that is conducive to industry-wide strategies. Furthermore, the risk posture, supplier and manufacturer interdependencies, and the supplier market have grown and thrived on vertical optimization and compartmentalization for many years. While the broader benefits of AI are tied to connectedness, moving forward in the near term will heavily depend on factory machine, and process level applications with immediate economic benefit for individual manufacturers to begin building a foothold in investment interest. It is AI's predictive capacity across the range of data centric modeling, and ultimately digital twins, that was emphasized.

The expectation for Workshop 2 is to provide a more detailed evaluation of the opportunities and challenges in applying AI for the wide ranging roles that formed the basis of this report:

- Industry-Wide Data Sharing
- Factory Floor Application
- Discovery of Capabilities and Solutions
- Building Resilient Supply Chains

The Implementation Framework offers an interrelated and interlinked R&D approach in which each of these four areas of AI opportunity can be further defined, aligned, and developed for each of the four areas of manufacturing implementation, but they must also be linked in an orchestrated development process at pace with continuous economic benefit. The objective is a virtuous research and development cycle that produces an AI development and implementation engine for manufacturing that drives manufacturing competitiveness.

Appendix A: Symposium and Workshop Plans

In early 2020, the National Science and Technology Council (NSTC) Subcommittee on Advanced Manufacturing and Subcommittee on Machine Learning and Artificial Intelligence articulated cross-agency interest in the strategic and timely value of organizing a symposium on a U.S. strategy for resilient manufacturing ecosystems through AI. Co-chairs, an organizing committee, and an advisory committee (please see Appendix B) were established and engaged in a process with both subcommittees to frame, shape, focus, and plan the symposium.

Considering the nature and complexity of the topic and with the aim of providing a comprehensive perspective, a three-workshop symposium was designed. The symposium brings together two communities: the advanced manufacturing community that is focused on the digitalization of manufacturing and the AI/ML community that is focused on applications, information technology, and computer science.

The overall goals of the symposium are to:

- Generate a cross-stakeholder consensus on AI for achieving U.S. manufacturing resilience, economic competitiveness, reduced energy consumption, and cyber/data security, and
- Set the stage for the two communities to collaborate on a roadmap that lays out a national strategy for a three-year horizon that places R&D needs in a comprehensive context.

The following three workshops were planned:

Workshop 1: Aligning Artificial Intelligence and U.S. Advanced Manufacturing Competitiveness

- What is resilience for manufacturing ecosystems balanced with competitiveness, resource consumption, demand and supply shocks, and national cyber and data security?
- What U.S. resilience elements are strong, weak, or missing in a digitalization context? Which are near term priorities? What about advanced manufacturing drives value for AI?

Workshop 2: AI Technologies, Practices, Workforce Needs, and National R&D Priorities for Manufacturing

- What are the enabling solutions for integrating resilience with all national manufacturing priorities? Where is AI the right solution and where is it not? What R&D is needed?
- What workforce capabilities are needed and what else or what other factors need to be addressed for AI R&D to be implemented successfully? What are the challenges?

Workshop 3: Comprehensive Roadmap for a Three-Year Horizon

- What are the dimensions of a comprehensive plan for implementing AI in U.S. advanced manufacturing that make up a national workforce, technical, practice, and operational strategy and roadmap?

Each workshop is standalone with respect to important objectives and reportable outcomes but connected to the others to achieve a fuller, more comprehensive outcome. A list of the symposium and workshop organizers is provided in Appendix B. The organization and the workshop program are included in Appendix C. A list of Workshop 1 participants is provided in Appendix D.

Appendix B: Symposium Leadership

Co-Chairs

Jim Davis: Vice Provost IT, Office of Advanced Research Computing, UCLA, and Program Oversight, Clean Energy Smart Manufacturing Innovation Institute (CESMII)

Stephan Biller: CEO & President, Advanced Manufacturing International, Inc.

Charles Romine: Director of the Information Technology Laboratory, NIST

Organizing Committee

Said Jahanmir: Assistant Director for Federal Partnerships, Office of Advanced Manufacturing, NIST

Faisal D'Souza: Networking and Information Technology Research and Development (NITRD) Program of the NSTC

Lisa Fronczek: Associate Director, Advanced Manufacturing National Program Office, NIST

John Roth: Assistant Director for Research Partnerships, Advanced Manufacturing National Program Office, NIST

Don Ufford: Advanced Manufacturing Policy Fellow, Advanced Manufacturing National Program Office, NIST

Interagency Advisory Committee

Mike Molnar, Frank Gayle: Advanced Manufacturing National Program Office, NIST

Sudarsan Rachuri: Advanced Manufacturing Office, DOE

John Vickers: NASA

Bruce Kramer: Directorate for Engineering, NSF

Andy Wells: Directorate for Engineering, NSF

Astrid Lewis, Aubrey Paris: Department of State

Kim, Young Ah: Department of Homeland Security

Chuck Geraci: NIOSH

Charles Romine: NSTC, ML/AI Subcommittee

Henry Kautz: Directorate for Computer and Information Science and Engineering and NITRD AI R&D Interagency Working Group (IWG)

David Miller: Directorate for Computer and Information Science and Engineering and NITRD Intelligent Robotics and Autonomous Systems IWG

Manufacturing USA Advisory Committee

John Wilczynski: America Makes

Gary Fedder: ARM

Alexander Titus: ARMI/BioFabUSA

John Dyck, Haresh Malkani: CESMII

John Hopkins: IACMI

Nigel Francis, Hadrian Rori: LIFT

Chandra Brown, Federico Sciammarella: MxD

Scott Miller, Janos Veres: NextFlex

Kelvin Lee: NIIMBL

Bill Grieco: RAPID

Appendix C: First Workshop Organization

The first workshop was sponsored by the National Science Foundation and the National Institute of Standards and Technology, and hosted by the University of California, Los Angeles (UCLA). The virtual workshop was convened on December 2, 2020 and continued on December 4, 2020.

The workshop had two specific goals:

1. Construct a scan of priority opportunities, challenges, and collaboration points for AI/ML for U.S. advanced manufacturing competitiveness
2. Generate a table of opportunities, challenges, and collaboration points to be considered in depth in a future workshop

This workshop emphasized four overarching manufacturing areas of emphasis related to digitalization so that the workshop participants could consider the relative impacts and roles for AI and ML in advanced manufacturing:

1. Facilitating the manufacturing ecosystem and supply chain restructuring, connectedness, visibility, interoperability, and agility for global competitiveness, and preparing for and responding to global and national disruptions;
2. Envisioning greater performance and precision in advanced process and machine operations as assets in resilient manufacturing ecosystems;
3. Building a broadly skilled, data-savvy workforce that can be more flexibly deployed; and
4. Enabling industry data flow and exchange, cyber opportunity, and national cyber and data security.

To achieve the goals of the symposium as outlined in Appendix A, the first workshop comprised four distinct parts: introductory remarks, panels, workgroup sessions, and report-outs. These parts involved a multi-stakeholder group of participants from across many sectors. Utilizing a public-private partnership model, this workshop gathered input from participants to understand the unique nexus of AI and the manufacturing sector.

Introductory remarks on Day 1 of the workshop were made by the co-chairs. These remarks set the stage for the entirety of the workshop. The co-chairs focused on the task ahead for the participants to define the challenges of the manufacturing sector as well as potential opportunities for AI to meet those challenges. Day 2 introductory remarks were made by UCLA's Executive Vice Chancellor and Provost Emily Carter, who focused on the importance of bringing together industry, academia, and government partners to tackle the challenges of tomorrow.

The workshop included two panels, one focused on the challenges of the manufacturing sector, and one focused on the opportunities presented by AI. An invited panel of manufacturing experts discussed the definition of resilience for manufacturing ecosystems considering economic competitiveness, energy and material consumption, demand and supply shocks, and national cyber and data security, using the lens of digital transformation. An invited panel of experts from the AI/ML community reflected on the discussion of the first panel and how manufacturing challenges and opportunities are viewed from an AI/ML perspective by addressing overarching questions.

Panel 1. Manufacturing Challenges

Susan Smyth (co-moderator), SME President, U.S. Army Science Board, GM Chief Scientist for Manufacturing (Retd)

Stephan Biller (co-moderator), CEO & President, Advanced Manufacturing International, Inc.

Jeff Kent, Vice President, Smart Platforms Technology & Innovation, Procter & Gamble

Michele C. D'Alessandro, Vice President and CIO, Manufacturing IT, Merck & Co., Inc.

Çağlayan Arkan, Vice President, Manufacturing Industry, Microsoft Corp.

John Dyck, CEO, CESMII – The Smart Manufacturing Institute

Panel 2. Artificial Intelligence/Machine Learning (AI/ML) Opportunities

Lynne Parker (moderator), Deputy Chief Technology Officer of the United States, and Assistant Director for Artificial Intelligence (AI), White House Office of Science and Technology Policy

Ed Abbo, President and CTO, C3.ai

Jayant Kalgnanam, Director, AI Applications (Asset Mngt & Supply Chain), IBM Research; Distinguished Industry Leader (2020), Chemicals & Petroleum & Industrial Products

Daniela Rus, Director, Computer Science and AI Laboratory (CSAIL); Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science; and Deputy Dean of Research, Schwarzman College of Computing, MIT

Reid Simmons, Research Professor in Robotics and Computer Science, Carnegie Mellon University

With the topics introduced by the co-chairs and panels, the workshop turned to the participants to provide feedback in three facilitated breakout sessions. These sessions were designed to gather perspectives from both the manufacturing and AI/ML sectors into what opportunities and challenges exist in leveraging AI in the advanced manufacturing sector. Below are the three session topics with their respective questions.

Breakout Sessions

Session 1: National/global scale considerations for manufacturing ecosystems, supply chains, and data flows

a. What U.S. ecosystem and supply chain elements are strong, weak, or missing?
b. What impacts has the Covid-19 pandemic revealed for U.S. advanced manufacturing resilience?
c. How do national and global considerations impact the manufacturing ecosystem and data flow considerations?
d. Where do AI/ML versus other approaches stand as solutions, and why?
e. Why would the AI community be interested in these problems, and what would they need to understand about the problems?

Session 2: Local factory operation and workforce considerations where solutions are ultimately implemented

a. What U.S. factory and workforce elements are strong, weak, or missing in a digital transformation context?
b. What have the Covid-19 impacts revealed for factory and workforce considerations?
c. How do national and global considerations and ecosystem and data flow considerations come together in local factory and workforce considerations?
d. Where do AI/ML versus other data and modeling approaches stand as solutions, and why?
e. What needs to be true for the new data and modeling tools to be accessible to the workforce and for the workforce to use them?
f. Why would the AI community be interested in these problems, and what would they need to understand about the problem?

Session 3: Bringing ecosystems, data flow, factory operations, and workforce together; addressing priorities and cross-cutting AI/industry opportunities and challenges; and collaboration points

a. What are the priority AI opportunities and challenges?

b. What are categorical use cases that showcase opportunities and challenges?
c. What needs to be true for AI opportunities in advance manufacturing to scale?
d. What does the manufacturing community need from the AI community, and why would the AI community be interested?
e. What structural changes are needed in the industry and its stakeholders?
f. What collaboration points between and among industry, academia, and government are needed?
g. What is in the opportunity table after the scan?

Following each breakout session, moderators shared brief reports that contained the salient points discussed at the sessions they moderated. These reports served as a transparent way to leverage all information across the breakout sessions among workshop participants.

Appendix D: Workshop 1 Participants

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