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NSF Engineering Research Visioning Alliance

Engineering the Future of Distributed Manufacturing

Executive Summary


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Executive Summary

For nearly 50 years, the narrative surrounding manufacturing in the United States has been one of overall decline. In 1960, the United States was the undisputed leader in world trade with the most international trade partners; by 2020, China had become the world's dominant trade partner. As of 2021, the United States/China trade deficit stood at $335 billion. Manufacturing has endured a loss of over 30% of jobs since 1970, and its share of national gross domestic product has shrunk from 27% to 12%.

Today, only 8.6% of the national workforce (12.75 million people) is employed by manufacturing companies nationwide. Many of these approximately 591,000 companies are small businesses; over 75% have fewer than 20 employees. In the early days of the COVID-19 pandemic, consumers faced empty shelves and extended delays for items as basic and essential as toilet paper and household cleaning products. Americans were confronted with the fragility of U.S. manufacturing when disrupted production and broken supply chains could not meet the demand for goods domestically and globally.

Although several key government actions have targeted manufacturing, including the 2022 CHIPS and Science Act, revitalizing the sector for long-term growth in the United States seems a herculean task. The dedicated facilities and human-intensive production lines of traditional manufacturing can no longer compete with smart manufacturing, often termed Industry 4.0, which is dominated by production activities that implement cyber-physical systems, the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) and machine learning (ML). Nor are such facilities prepared for the shift that some are designating Industry 5.0, which will combine human and machine intelligence to create a more streamlined, human-centered, and personalized consumer experience.

The engineering research community can lead in changing the trajectory of U.S. manufacturing. It is essential to identify, scale up, and integrate critical technologies for new and emerging advanced manufacturing sectors to create a secure, resilient, and adaptable manufacturing ecosystem. Doing so will contribute to a more flexible and secure economy in the 21st century and beyond. **Innovative, resilient, and future-driven engineering research must mobilize across three key areas—materials; processes and tools; and data for process/quality control—to**

create avenues for U.S. manufacturers to improve their productivity, agility, and competitiveness. Such research should produce scalable and affordable advances in these areas so that small and mid-sized manufacturers can access and operationalize these advances to spur income growth, new jobs, local investment, and innovation across the ecosystem.

This was the consensus reached by 56 participants representing small- to medium-sized manufacturing companies as well as researchers and technical experts from industry, government, and academia assembled at the March 30-31, 2023 visioning event convened by the Engineering Research Visioning Alliance (ERVA). The goal was to identify critical areas for engineering research in distributed manufacturing in topics defined by the event's Thematic Task Force; in particular, discrete manufacturing for components with structural performance criteria. Of note, the scope of this report did not extend to include another key area of opportunity for distributed manufacturing – distributed chemical manufacturing. The common thread across all discussion was engineering resiliency with respect to three topics:

- **Materials supply chains** that are secure and distributed;
- **Tools and processes** to create any discrete manufacturing product/tool anywhere, anytime, and in any lot size, without loss of quality; and
- **Data and quality assurance** engineering research to improve the efficiency of production processes regardless of lot size, optimize inventory management, reduce downtime, and enhance the quality of products and services.

During the breakout sessions, participants generated a dozen grand challenges within and across these topic areas to prioritize for engineering research investment. These are listed below and explained in more detail in this report.

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Grand Challenges

Materials Supply Chains

- Design next-generation materials for manufacturing to enable synthesis of non-polluting, recyclable, and renewable materials.
- Improve new materials qualification/certification processes by developing normalized descriptions and a database for physical properties and characteristics, such as cost, availability, and supply chain robustness.
- Reduce waste throughout the materials life cycle, seeking the ideal of cradle-to-cradle life cycles.

Tools and Processes

- Design new systems based on adaptive control, closed-loop, and beyond.
- Develop swarm manufacturing to enable use of multiple small tools, subtractive/additive/form/join/impact/metrology.
- Create open-source hubs that use normalized terminology and share aggregated, de-identified tool data for knowledge integration among manufacturers; aggregated data can be provided to the academic community for study and development.

Data and Quality Assurance

- Increase and share in-process manufacturing data exponentially.
- Develop in-situ quality assurance tools.
- Enable model-based material and component certification.

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Taking Action

Current and future research should generate rapid innovation that enables the United States to lead in advanced manufacturing. Developing and implementing critical technologies in materials and supply chains; tools and processes; and data collection and measurement will enable manufacturers of all sizes to operate efficiently and safely both in normal and exceptional conditions. Research into the following five overarching areas should generate rapid, sustained innovation that enables the United States to lead in advanced manufacturing.

Engineer new, sustainable materials for use in advanced manufacturing

Research into optimizing manufacturing methods to guarantee quality across manufacturing locations—with local access to different raw material sources of varying quality—is imperative. Qualification and certification processes must evolve to account for advances in materials, processes, and lot sizes. For raw materials, learning from nature to develop bio-based feedstocks, alloys, or composite materials to replace difficult-to-obtain materials will aid in improving supply chain resilience and reduce the carbon footprint of manufacturing processes. As these new materials are developed, creating centralized databases of material recipes, including ingredients, tools, and mixing parameters, will be critical to enabling uniform quality. Consistent characterization of material content and properties will also aid in improving quality control and recycling methods for these materials.

Enable new business models that better manage supply chains to build resilience, minimize disruption, and reduce wasted time and materials

Increasing supply chain viability requires increasing and leveraging analytics capability in all phases, including planning, market conditions, procurement, transportation, and manufacturing facilities. Opportunity exists for engineering research to create simulation environments to decrease capture, analysis, and decision latency so information about supply chain events is better understood and acted upon across all sectors in the chain.

Re-envisioning supply chain dynamics will also help manufacturing decarbonize and move toward a more circular economic model. While many definitions exist, a circular economy is often characterized as a regenerative system with little or no pollution or waste, where materials, products, components, and by-products are used to their fullest capacity for the longest time. Creating large-scale circular economies for manufacturers will require changes to all phases of supply chains to develop materials that will be plentiful and that can be up- or downcycled to extend their useful lifespans. It will require research into new machinery that uses energy more efficiently while generating less waste. And it will require research to develop new materials that can alleviate the strain in many critical material supply chains.

Design next-generation machines that are small, agile, and reconfigurable

Manufacturing companies that employ 20 or fewer people generally lack the resources to pivot quickly in response to technological change. Tools and processes alike are compartmentalized, mostly closed architectures that are often an afterthought as new products are designed. Research opportunities abound in designing tools and machines for distributed manufacturing. Examples include researching the potential of machine neural networks for distributed machining of large parts or end products, or researching self-assembly of parts, including modalities for doing so. Manufacturing software represents another area; can AI be leveraged to produce a "ChatGPT" for parts manufacturing? Provisioning software through the cloud rather than relying on local resources can also reduce obsolescence and make the updates more affordable. And collaborative research on human-machine optimization for a variety of environments, from the single user to assembly line production, may present new possibilities for all company sizes.

Create common, effective, and affordable standards for data collection, analysis, and communication

The ability to collect and turn data into useful knowledge in real time has exponentially increased in the last 20 years, yet much potential across manufacturing remains largely untapped for proprietary reasons. Research is essential to determine what data is useful and the appropriate standards and formats for collecting and storing data while respecting individual companies' privacy concerns. Current and next-generation manufacturing operations will require effective, standardized methods for storage management and for open source data sharing as appropriate. Analysis technologies must be envisioned, developed, and implemented to create visualization tools for modeling; similarly, algorithms must be developed to assimilate disparate data into actionable decisions. Looking forward, researchers can leverage research opportunities for both mature and emerging technologies to infuse data analytics with manufacturing mindsets. Advances in hardware, software, cybersecurity, and data standardization will require experts in those and allied areas to envision and implement equitable, trustworthy, and accessible systems to serve those employed in all manufacturing areas. These advances will enable learning and protect against cybersecurity attacks without negatively impacting U.S. technology competitiveness.

Develop greater connectivity across the sector and work to eliminate silos

U.S. manufacturing is at a critical juncture as it looks to regain a position of global leadership in manufacturing. Concerted efforts must emanate from all parts of the sector, including small- and mid-size producers, dominant corporations, academia, and government, to innovate and question all aspects of operations in search of transformational advances. Distribution and compartmentalization of knowledge across manufacturing has contributed to widespread perception outside the industry that manufacturing is more a part of our nation's past than its future.

Engineering research can help break that cycle by integrating research that improves current materials, tools, and processes with new manufacturing technologies and interoperable data-driven decision-making. Engineering research can also play a key role in attracting the next generation of higher level manufacturing professionals as they recognize the complexity of the 21st-century manufacturing industry. This report aims to inspire researchers and funders (public, private, and nonprofit) to support and pursue these engineering research priorities.

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Our mission is to identify and develop bold and transformative new engineering research directions and to catalyze the engineering community's pursuit of innovative, high-impact research that benefits society.

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