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EMBRACING THE FUTURE: HOW TO CAPITALIZE ON ADVANCED MANUFACTURING

INDUSTRY STUDY – ADVANCED MANUFACTURING COURSE PAPER

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Executive Summary[1]

The United States (U.S.) must revitalize its manufacturing base to maintain national security and economic competitiveness in an era of great power rivalry and technological change. This study by the Eisenhower School's Industry Study on Advanced Manufacturing (AM) argues that AM technologies—spanning additive manufacturing, advanced materials, industrial artificial intelligence, robotics, the internet of things, digital threads, accelerated computing, advanced modeling and simulations, and augmented reality / virtual reality—are essential for restoring America's industrial capacity and ensuring the agility and resilience of the defense industrial base (DIB).

Today, while the U.S. retains global leadership in innovation and high-end research and development, its production capabilities, especially in defense-critical sectors, face severe constraints due to aging infrastructure, dwindling small and medium manufacturers (SMM), brittle supply chains, and persistent workforce shortages. The Department of Defense (DoD) remains heavily reliant on a fragile network of these SMM, which often lack access to the capital and expertise required to adopt AM technologies.

Comparative analysis with China, Russia, and France highlights the strategic urgency. China's top-down, state-driven "Made in China 2025" initiative has rapidly scaled industrial innovation centers and digital infrastructure. Russia, despite limited capacity, demonstrates how unmodernized defense manufacturing struggles to support sustained conflict. France offers a middle path, emphasizing sustainability, workforce training, and regional industrial policy.

[1] OpenAI, *ChatGPT*, accessed May 14, 2025, https://chat.openai.com. The authors used ChatGPT to assist in drafting the executive summary of this paper; all content was reviewed and revised by the editor for accuracy and clarity.

The adoption of AM technologies across the commercial and defense sectors is vital not only for economic productivity but for warfighting readiness. After a detailed analysis of AM across four critical themes: technology, supply chain, workforce, and industrial policy, the paper proposes seven policy recommendations that address both whole-of-government and DoD-specific efforts. They are deliberately narrow in scope and should be considered as augmenting, rather than replacing, existing policy efforts. The policy recommendations are:

Whole of Government

- Technology: Provide SMM with access to Government-furnished, Leased AM equipment through direct grants, subsidized leases, and shared-access facilities.
- Supply Chain: Strengthen U.S. Supply Chain Resilience Through Public-Private Partnership and Prioritization
- Workforce: Expand E3 immigrant visa opportunities for legal immigrants to work in manufacturing jobs.
- Industrial Policy: Renew and expand the Strengthening Community Colleges Training Grants (SCCTG).

DoD

- Technology: Leverage existing DoD funds to incentivize the adoption of AM technology within the DIB.
- Supply Chain: Invest in providing Cybersecurity Maturity Model Certification (CMMC) compliant networks to SMM to grow the DoD supply chain.
- Workforce: Revector the mission of the Office of Local Defense Community Cooperation to leverage the 800+ military facilities across the U.S. and align local, state, and federal resources geared toward manufacturing.

Urgent, coordinated action is needed to modernize the U.S. industrial base. Without targeted investments in AM technologies, the U.S. risks losing its ability to respond to large-scale conflicts and to out-innovate its strategic competitors. Revitalizing the manufacturing sector through smart industrial policy, agile public-private collaboration, and a resilient workforce will ensure the U.S. remains the world’s preeminent industrial and military power.

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Industry Site Visits and Guest Speakers

Guest Speakers
- National Institute of Standards & Technology (NIST)
- Global Foundries
- Office of Naval Research
- Ayer Labs
- MMR Defense Solutions, LLC
- Purdue University
- Marque Ventures
- DARPA
- OSD ManTech
- MIT

DC, Maryland, Virginia Site Visits
- NIST
- Xometry
- Thales Defense & Security, Inc (TDSI)
- Palantir
- Anduril

Tennessee Site Visits
- Oak Ridge National Laboratory
  - Carbon Fiber Technology Facility
  - Manufacturing Demonstration Facility
- Ridge National Laboratory National Transportation Research Center
- Industrial Plastic Works
- Dienamic Tooling Systems, Inc
- Institute for Advanced Composites Manufacturing Innovation (IACMI), *Manufacturing USA Institute on Composites*
  - IACMI Collaboration Facility, South Campus
  - Tennessee Manufacturing & Design Enterprise Facility, *University of Tennessee partnership*

New York Site Visits
- American Institute for Manufacturing Integrated Photonics (AIM Photonics), *Manufacturing USA Institute for Photonics*
- Tokyo Electronics Corporation (TEL)
- IBM Research
- GE Aerospace Research

California Site Visits
- NetFlex, *Manufacturing USA Institute on Additive Hybrid Electronics*
- Stanford Linear Accelerator Center (SLAC) National Accelerator Lab
- The Gordian Knot Center for National Security Innovation, *Stanford University*
- Gooch & Housego (G&H)
- Stanford Additive Manufacturing & Prototyping Facility, *Stanford University*

Illinois Site Visits
- Oracle Innovation Lab
- Northrup Grumman
- Argonne National Laboratory
- Manufacturing x Digital (MxD), *Manufacturing USA Institute on Digital Manufacturing and Cybersecurity*
- ARCtronics
- GAM Enterprises
- IMEC, *Manufacturing USA MEP for Illinois*
- Lawrence Foods

France Site Visits
- Safran Electronics & Defense
- Thales Group
  - Headquarters
  - Division 6
- KNDS
  - Ammunition France
  - Arms Factory
- DGA Land Technical Center
- NATO Science & Technology Organization
- US Embassy to France

Acronym List

ADMAN – additive manufacturing

AI – artificial intelligence

AM – advanced manufacturing

AMEAP – Advanced Manufacturing Equipment Access Program

CAD – computer aided design

CHIPS – Creating Helpful Initiatives to Produce Semiconductors

CMMC – Cybersecurity Maturity Model Certification

CSIS – Center for Strategic and International Studies

CTE – Career Technical Education

DIB – defense industrial base

DLA – Defense Logistics Agency

DOC – Department of Commerce

DoD – Department of Defense

DOE – Department of Energy

ERP – enterprise resource planning

EU – European Union

EUV – extreme ultraviolet

GDP – gross domestic product

GenAI – generative artificial intelligence

IoT – internet of things

IP – intellectual property

IRA – Inflation Reduction Act

IT – information technology

IV – immigrant visas

MEP – Manufacturing Extension Partnership

MES – manufacturing execution system

MIC – Manufacturing Innovation Centers

ML – machine learning

M&S – modeling and simulation

NATO – North Atlantic Treaty Organization

NIST – National Institute of Standards and Technology

NY – New York

OLDCC – Office of Local Defense Community Cooperation

OSD – Office of the Secretary of Defense

OT – operational technology

PA – Pennsylvania

PPP – public-private partnerships

R&D – research and development

SCCTG – Strengthening Community Colleges Training Grants

SMM – small and medium manufacturers

SOC – Standard Occupational Classification

TTX – tabletop exercise

U.S. – United States

WWII – World War II

A Rebirth for Manufacturing

Advanced manufacturing (AM) is essential to reviving America's industrial base and sustaining its global military advantage. As strategic competitors invest in next-generation manufacturing, United States (U.S.) national security depends on accelerating the adoption of AM technologies across both commercial and defense sectors. But decades of disinvestment, offshoring, and workforce atrophy have hollowed out the once vaunted "Arsenal of Democracy" and called into question the defense industrial base's (DIB) ability to meet the demands of a peer competition. There are many stakeholders invested in this sector (see Appendix C: Stakeholders) and overcoming these challenges requires a comprehensive approach that addresses technological capabilities, workforce development, supply chain resilience, and industrial policy coordination.[2] The revitalization of American manufacturing hinges on successfully navigating the adoption and implementation of AM to fully embrace the fourth industrial revolution and reaffirm the U.S. as a manufacturing power capable of sustained military action anywhere in the world.

This paper begins with a historical overview of U.S. manufacturing, before briefly assessing the current state of the industry after recent efforts to revive it. Next, the paper provides a robust analysis for the industry across four central themes—technology, supply chain, workforce, and industrial policy. Following that, it surveys the international environment through the same four lenses, with a particular focus on China, Russia, and France. After reviewing the global outlook, the paper concludes with specific policy recommendations to accelerate the U.S.'s AM transition.

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[2] There are many types of industrial policy within the United States, let alone the world. For brevity's sake, this paper will focus specifically on the concept of the Triple Helix. For a more comprehensive listing of applicable industrial policies, please refer to Appendix E: U.S. AM Policies.

ADVANCED MANUFACTURING AND NATIONAL SECURITY

"Manufacturing is an engine of America's economic strength and national security. It plays a vital role in almost every sector of the United States economy, from aerospace to biopharmaceuticals and beyond. Advances in manufacturing enable the economy to continuously grow as new technologies and innovations increase productivity, enable next-generation products [...] and create new, high-quality, and higher-paying jobs." – National Strategy for Advanced Manufacturing, October 2022[33]

"The war in Ukraine highlights the criticality of a vibrant Defense Industrial Base for the United States and its allies and partners. It must not only be capable of rapidly manufacturing proven capabilities needed to defend against adversary aggression, but also empowered to innovate and creatively design solutions as battlefield conditions evolve." – National Security Strategy, 2022[44]

"The Department [of Defense] will act urgently to better support advanced manufacturing processes to increase our ability to reconstitute the Joint Force in a major conflict." – 2022 National Defense Strategy[55]

Historical Context

The transformative potential of American manufacturing emerged during World War II (WWII) as the U.S. mobilized to become the "Arsenal of Democracy," producing unprecedented quantities of military equipment that proved decisive in securing the Allied victory. This manufacturing triumph catapulted the U.S. to global economic dominance. With much of the industrialized world recovering from war devastation, American factories enjoyed unrivaled

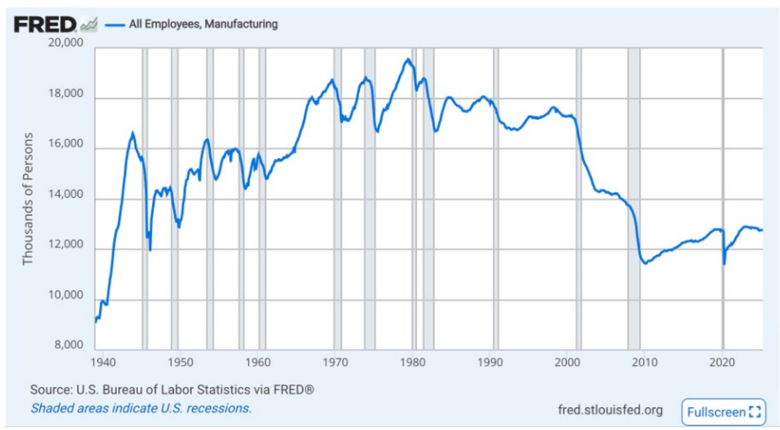
[3] National Science and Technology Council, *National Strategy for Advanced Manufacturing* (Washington, DC: Executive Office of the President, October 2022), https://www.manufacturing.gov/sites/default/files/2022-10/FINAL%20National%20Strategy%20for%20Advanced%20Manufacturing%2010072022%20Approved%20for%20Release.pdf. Although these policies were implemented during the previous administration, they are still the most current strategic documents available. Due to previous bipartisan support for revitalizing manufacturing and the pressing national security threats, no dramatic shift in policy affecting advanced manufacturing is anticipated.

[4] President of the United States, *National Security Strategy* (Washington, DC: The White House, October 2022), https://www.whitehouse.gov/wp-content/uploads/2022/10/Biden-Harris-Administrations-National-Security-Strategy-10.2022.pdf.

[5] U.S. Department of Defense, *2022 National Defense Strategy of the United States of America* (Washington, DC: Department of Defense, October 2022), https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.pdf.

production. By 1946, manufacturing employed approximately 32% of the labor force, totaling 12.7 million workers, and just a year later, contributed over 25% of the nation's total Gross Domestic Product (GDP).[6]

The post-WWII era represented the golden age of American manufacturing with GDP eventually reaching 40% of global output by 1960, a position it maintained for nearly a decade.[7] This dominance culminated in 1979 when U.S. manufacturers employed their peak of 19 million people.[8] However, America's period of manufacturing preeminence fostered complacency as efforts to establish innovation ecosystems treated manufacturing as an afterthought to product development.[9] Additionally, a nationwide push toward college education created a pervasive stigma against traditional trade skills like manufacturing.[10]



Manufacturing Employment, 1940-2023

Meanwhile, other nations began to industrialize rapidly,

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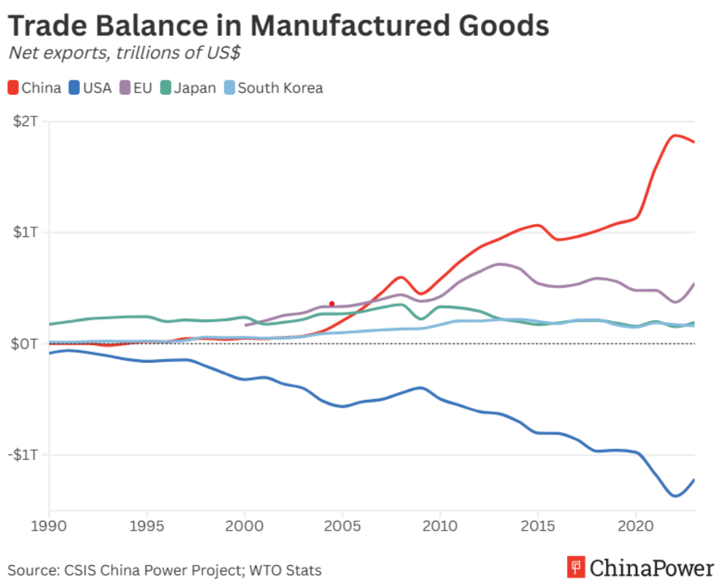
[6] Robert E. Yuskavage and Mahnaz Fahim-Nader, "Gross Domestic Product by Industry for 1947–86: New Estimates Based on the North American Industry Classification System," *Survey of Current Business* (December 2005): 70=84, https://apps.bea.gov/scb/pdf/2005/12December/1205_GDP-NAICS.pdf. Historical data for industry-specific contributions to GDP does not exist prior to 1947.

[7] Mike Patton, "U.S. Role In Global Economy Declines Nearly 50%," *Forbes*, February 29, 2016, https://www.forbes.com/sites/mikepatton/2016/02/29/u-s-role-in-global-economy-declines-nearly-50/.

[8] U.S. Bureau of Labor Statistics. *Civilian Labor Force Level*. Retrieved from FRED, Federal Reserve Bank of St. Louis. Accessed April 4, 2025. https://fred.stlouisfed.org/series/CLF16OV;
U.S. Bureau of Labor Statistics, *All Employees, Manufacturing/All Employees, Total Nonfarm* [Graph], retrieved from FRED, Federal Reserve Bank of St. Louis, accessed April 20, 2025, https://fred.stlouisfed.org/graph/?g=cAYh.

[9] U.S. Bureau of Labor Statistics, All Employees, Manufacturing [MANEMP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/MANEMP, May 9, 2025. This note accompanies the graph, not the text.

[10] David Adler and William B. Bonvillian, "America's Advanced Manufacturing Problem—and How to Fix It," *American Affairs* 7, no. 3 (Fall 2023), https://americanaffairsjournal.org/2023/08/americas-advanced-manufacturing-problem-and-how-to-fix-it/.



particularly in East Asia. Japan introduced just-in-time production and continuous improvement methodologies in the 1970s.[11] With favorable governmental policies, Japan began to undermine American dominance and created a blueprint that other "Asian Tigers" like South Korea and Taiwan soon followed. China amplified the practice by leveraging cheap capital, abundant labor, and targeted industrial policies to spur unprecedented industrial growth. China produced 29% of global manufacturing in 2023, valued at $4.66 trillion—more than the next four leading manufacturing countries combined.[12] Rather than try to compete by investing in domestic manufacturing, many U.S. companies outsourced production to their competitors. Once manufacturing jobs moved overseas, design and high-technology positions often followed.[13] The consequences compounded—by 2010, the U.S. shed 32% of its manufacturing jobs.[14]

This erosion had profound implications for America's communities. Cities like Rochester, NY, and Scranton, PA, lost 45% of their manufacturing jobs between 1980 and 2005.[15] Efforts to

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[11] Adler and Bonvillian, "America's Advanced Manufacturing Problem."
[12] China Power Team, "Measuring China's Manufacturing Might," *China Power*. December 17, 2024. Accessed April 23, 2025. https://chinapower.csis.org/tracker/china-manufacturing/. This is also the source of the graph at the top of the page.
[13] Waldon Bello, "From Partnership to Rivalry: China and the USA in the Early Twenty-First Century," *Journal of Contemporary Asia* 53, no. 5 (2023), 828-851, https://doi.org/10.1080/00472336.2023.2199760.
[14] Bello, "From Partnership to Rivalry."
[15] "American Factories Could Prosper If They Find Enough Skilled Workers," *The Economist*, accessed March 28, 2025, https://www.economist.com/business/2017/10/12/american-factories-could-prosper-if-they-find-enough-skilled-workers.

revitalize these communities through new manufacturing investments have sometimes failed to deliver on their promises. Wisconsin's 2017 deal with Foxconn involved $3 billion in state and local subsidies in return for a promised 13,000 jobs and a $10 billion corporate investment. As of 2024, less than 10% of the pledged positions have materialized, and Foxconn's capital investment totals only $1 billion, leaving residents feeling betrayed.[16]

Current Manufacturing Landscape

Today, manufacturing remains a significant sector of the U.S. economy despite its relative decline. It accounts for 11% of the GDP and employs 12.9 million people.[17] The sector drives 20% of U.S. capital investments, 30% of productivity growth, 60% of exports, and 70% of business investment in research and development (R&D).[18] It generates $2.6 trillion in value-added output, ranking second globally behind China's $5.1 trillion.[19] Despite the substantial output, annual investment growth averages 1-2%, consistently below overall GDP growth, driven by limited venture capital interest, high capital costs, and outsourcing.[20] This decline particularly affects small and medium-sized manufacturers (SMM) who constitute 98% of all manufacturing companies and account for 43% of the manufacturing workforce.[21] In the past decade 40% of small suppliers and 20,000 SMM have closed.[22]

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[16] Scott Cohn, "Wisconsin Wants to Be Tech Mecca. After Foxconn Broken Promises, the State Says This Time Is for Real," CNBC, June 25, 2024, https://www.cnbc.com/2024/06/25/wisconsin-wants-to-be-tech-mecca-and-leave-the-foxconn-fail-behind.html.

[17] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 2; U.S. Bureau of Labor Statistics, "All Employees, Manufacturing," FRED, Federal Reserve Bank of St. Louis, last modified April 4, 2025, https://fred.stlouisfed.org/series/MANEMP.

[18] Adler and Bonvillian, "America's Advanced Manufacturing Problem."

[19] Douglas Thomas, *Annual Report on the U.S. Manufacturing Economy: 2024*, Advanced Manufacturing Series (NIST AMS) 600-16 (Gaithersburg, MD: National Institute of Standards and Technology, October 25, 2024), 1, https://doi.org/10.6028/NIST.AMS.600-16.

[20] U.S. Department of Defense, *Securing Defense-Critical Supply Chains: An Action Plan Developed in Response to President Biden's Executive Order 14017* (Washington, DC: Office of the Assistant Secretary of Defense for Industrial Base Policy, February 2022), 64, https://media.defense.gov/2022/Feb/24/2002944158/-1/-1/1/DOD-EO-14017-REPORT-SECURING-DEFENSE-CRITICAL-SUPPLY-CHAINS.PDF.

[21] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 2.

[22] Industry Site Visit, April 3, 2025.

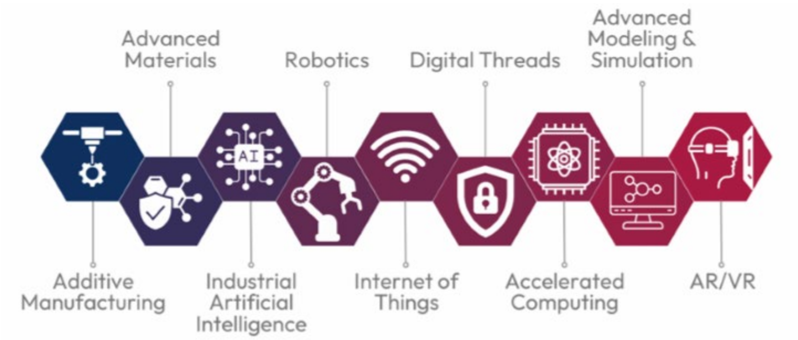
The challenges confronting the manufacturing industry writ large are even more acute for the DIB. Although dominated by the five primes, those companies depend on secondary and tertiary production from a shrinking network of SMM.[23] An estimated 86% of manufacturers surveyed earn less than 10% of their revenue from defense contracts, yet these SMM produce items essential to maintaining weapon systems.[24] As an example, a 2020 Defense Logistics Agency assessment determined that 30,061 out of 32,597 specialized end-items contain cast or forged components, with over 16,000 unfilled requests for quotation, most for quantities under 200 units.[25] The decline of domestic foundries by 67% since 2000 undoubtedly contributes to the unfilled requests,[26] especially given only one foundry can produce the large titanium castings required for certain defense systems.[27] The DIB has numerous other examples of unfilled orders and single source supply chains. AM technologies and newly trained workforce are one solution to meeting these needs and further enhance U.S. national security.

Advanced Manufacturing

Like its traditional manufacturing predecessor, AM is critical to sustaining the U.S. economy, but it also offers an opportunity to revitalize the DIB and ensure national security. The U.S. National Science and Technology Council defines AM as "the innovation of improved methods for manufacturing existing products, and the production of new products enabled by

[23] The five prime contractors are Lockheed Martin, Boeing, General Dynamics, RTX, and Northrup Grumman.
[24] U.S. Department of Defense, *Securing Defense-Critical Supply Chains*, 63.
[25] U.S. Department of Defense, *Securing Defense-Critical Supply Chains*, 25.
[26] National Center for Defense Manufacturing and Machining (NCDMM), *Additive Manufacturing Technology Roadmap for Casting and Forging* (Blairsville, PA: NCDMM Headquarters, August 2023), 1, https://www.americamakes.us/wp-content/uploads/2023/11/AM-Technology-Roadmap-for-Casting-Forging-Report-OCT23.pdf.
[27] U.S. Department of Defense, *Securing Defense-Critical Supply Chains*, 26. Global competition from China, which produces more cast metal tonnage than the next seven countries combined, has exacerbated these challenges. During an industry site visit on February 7, 2025, one tool and die maker noted that Chinese manufacturers can design and cast in 10 days at 30-40% lower cost.

advanced technologies."[28] AM options span a wide range of technologies including additive manufacturing (ADMAN), advanced materials, industrial artificial intelligence (AI), robotics, the



internet of things (IoT), digital threads, accelerated computing, advanced modeling and simulations (M&S), and augmented reality / virtual reality.[29] Leveraging these capabilities can produce faster, lower-cost, rapidly scalable manufacturing solutions, which enable innovative capabilities for the warfighter that sustain and strengthen the U.S.'s military preeminence.[30] (See Appendix D: AM Technologies)

U.S. Perspective

Historically, the U.S. innovation ecosystem excels at generating technological breakthroughs but struggles to transition these innovations into widespread production capabilities. This predilection originates in the aftermath of WWII when Vannevar Bush, the head of the U.S. Office of Scientific Research and Development during the war, advocated for a dispersed innovation ecosystem focused on basic research while military leaders of the day preferred an integrated system focused on application. The conflict over which approach was best overshadowed the importance of production entirely.[31] As a result, the era of domestic mass production gave way to one characterized by exquisite, high-end systems produced in limited

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[28] National Science and Technology Council, N*ational Strategy for Advanced Manufacturing*, 2.
[29] Brady Helwig and Addis Goldman, National Action Plan for United States Leadership in Advanced Manufacturing (Special Competitive Studies Project, June 2024), 5, https://www.scsp.ai/wp-content/uploads/2024/06/Advanced-Manufacturing-Action-Plan.pdf. The graphic is also from this text.
[30] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 4.
[31] Adler and Bonvillian, "America's Advanced Manufacturing Problem."

quantities at high cost. This is especially true for military systems, where individual platforms can cost billions of dollars. Shrinking Department of Defense (DoD) budgets and lessons from the Ukraine war—including munitions expenditure rates and the emergence of autonomous systems on the battlefield—are forcing a reconsideration of America's force mix and production capacity.

EMBRACING POSSIBILITIES

Non-traditional defense firms such as Anduril and Divergent are disrupting the defense industry by leveraging AM in innovative ways.[32]

Anduril plans to hyperscale weapons production using a software-designed manufacturing platform that will enable the flexibility to "reallocate the most critical manufacturing resources – people, capital, machines, and materials, to meet new requirements, launch new products, or scale production to meet surges in demand."[3233]

Similarly, Divergent is embracing emerging AM to modernize how it manufactures components and end items. Working with General Atomics, Divergent used AM to reduce a drone structure from 180 parts to 4.[3334]

These promising approaches are not without risk. AM technologies often face significant integration, scalability, and reliability challenges. The defense sector's high-mix, low-volume environment further complicates adoption, raising concerns that the AM revolution may, at times, overpromise and underdeliver without sustained investment, rigorous validation, and adaptive acquisition frameworks.[34]

Technology

Despite rapid advances in technology, technology adoption presents significant financial challenges for manufacturers. Technology investments accounted for approximately 30% of

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[32] Rory McDonald, Timothy Buehn, Aditi Ghai, and James Heffelfinger, *Disrupting Defense at Anduril Industries*, Harvard Business School Case 622-081 (June 2022, revised August 2022), 1.

[33] Eric Brothers, "Anduril to Build Hyperscale Manufacturing Facility," *Aerospace Manufacturing and Design*, January 17, 2025, accessed April 20, 2025, https://www.aerospacemanufacturinganddesign.com/news/anduril-to-build-hyperscale-manufacturing-facility/.

[34] Grace Harmon, "Modernizing Manufacturing: Divergent Raises $230M to Aid Growth," Los Angeles Business Journal, November 20, 2023, accessed April 21, 2025, https://labusinessjournal.com/featured/modernizing-manufacturing-divergent-raises-230m-to-aid-growth/.

manufacturing operating budgets in 2024, up from 23% in 2023.[35] Manufacturing requires investment capital for facilities, equipment, and materials but it typically takes longer to yield returns than software or services, making it less attractive to venture capitalists.[36] Recent economic conditions have further complicated investment decisions. While manufacturing experienced continued investment in 2024, higher interest rates created obstacles to near-term growth.[37] When modernizing, organizations must replace or upgrade legacy infrastructure while managing complex integrations between new systems and existing equipment, creating technical challenges and driving additional costs. Higher costs make capital-intensive investments in AM technology challenging for firms with limited resources.[38]

Unsurprisingly, adoption into manufacturing processes often lags technology development due to the high cost. Additionally, the motivation for adoption varies by sector. Defense companies frequently point to cost and schedule savings as drivers for automation, whereas private companies typically express a desire to increase product quality.[39] One defense prime manufacturer uses Scalable Composites Robotic Additive Manufacturing to make cheaper tooling through additive and fiber placement, reducing a 12-month forging lead time for a titanium part down to six weeks while also consolidating it from four components into a single part.[40] The newest manufacturing techniques are typically found in the manufacturing of new products that are high-volume — low-mix. As one small electronics manufacturer stated, speed is not as important as flexibility when dealing with high-mix—low-volume (as the DoD does).[41] This combination allows companies to

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[35] Deloitte Research Center for Energy & Industrials, *2025 Manufacturing Industry Outlook* (Washington, DC: Deloitte, November 20, 2024), 4, https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-outlook.html.
[36] U.S. Department of Defense, *Securing Defense-Critical Supply Chains*, 64.
[37] Deloitte Research Center, *2025 Manufacturing Industry Outlook*, 1.
[38] Deloitte Research Center, *2025 Manufacturing Industry Outlook*, 1.
[39] Industry Site Visit, April 2, 2025.; Industry Site Visit, April 4, 2025.
[40] Industry Site Visit, March 27, 2025.
[41] Industry Site Visit, April 4, 2025.

design for modern manufacturing from the beginning of the product's life and provides a return on investment to manufacturers who employ new technologies.

It is often cost-prohibitive for companies with high-mix—low-volume production to invest in new production technology, unless it can be used across multiple products. As a disruptive defense manufacturer observed, tool obsolescence carries a cost.[42] Three of the top seven opportunities identified in industry research aim to remove conventional tooling constraints, with the highest-ranked opportunities highlighting tools that reduce uncertainty in design and technology selection.[43] Tools like digital inventory management and production tracking software are examples of technologies applicable across multiple product lines. But even within these parameters, technology adoption still faces many challenges.

The technical characteristics of traditional manufacturing evolved with specialized equipment and techniques that do not easily translate into digital environments. For instance, accurately simulating metallurgical processes requires intensive computing resources that many manufacturers find prohibitively expensive.[44] Legacy components defined only on paper lack the 3D models needed for effective digitization, while underdeveloped material property standards create skepticism about simulation reliability compared to traditional processes.[45] Effective AM depends on data quality, with nearly 70% of manufacturers identifying data collection and validation as significant implementation barriers.[46] A small automation component manufacturer

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[42] Industry Site Visit, March 13, 2025.
[43] NCDMM, *Additive Manufacturing Technology Roadmap*, 22.
[44] Li Zhang, Xiaoqi Chen, Wei Zhou, Taobo Cheng, Lijia Chen, Zhen Guo, Bing Han, and Longxing Lu, "Digital Twins for Additive Manufacturing: A State-of-the-Art Review," *Applied Sciences* 10, no. 23 (2020): 4, https://doi.org/10.3390/app10238350.
[45] NCDMM, *Additive Manufacturing Technology Roadmap*, 21.
[46] Deloitte Research Center, *2025 Manufacturing Industry Outlook*, 4.

noted the quantity of data they generate does not warrant the investment, referring to their adoption of AM practices as "Industry 4.0 Lite."[47]

These challenges are especially prevalent in the DIB. Defense procurement practices create unique economic barriers to AM technology adoption. The cyclical demand and high-mix —low-volume nature of DoD procurement creates uncertainty in the supply chain, limiting companies' willingness to invest in new technologies.[48] Idle capacity is not an allowable cost on government contracts, disincentivizing the DIB from acquiring capital that cannot be used on existing contracts.[49] The Defense Federal Acquisition Regulation Supplement identifies a Technology Incentive Range that allows for higher profits when developing advanced technology, but there are currently no provisions to allow for higher profit margins when utilizing AM technologies.[50]

Perhaps the most significant barrier is the qualification and certification process for defense components. Qualification procedures remain prohibitively expensive and time-consuming, particularly for legacy components lacking digital definitions.[51] One military service research lab acknowledged the reluctance of technical warrant holders to take risks on novel parts.[52] Another SMM stated that design may not want to go through the requalification process (e.g., a Federal Aviation Administration-approved circuit board for aircraft). Current standards focus on replicating traditional manufacturing methods rather than ensuring functional requirements are met, creating inefficiencies in the transition to digital processes. Yet, significant manufacturing

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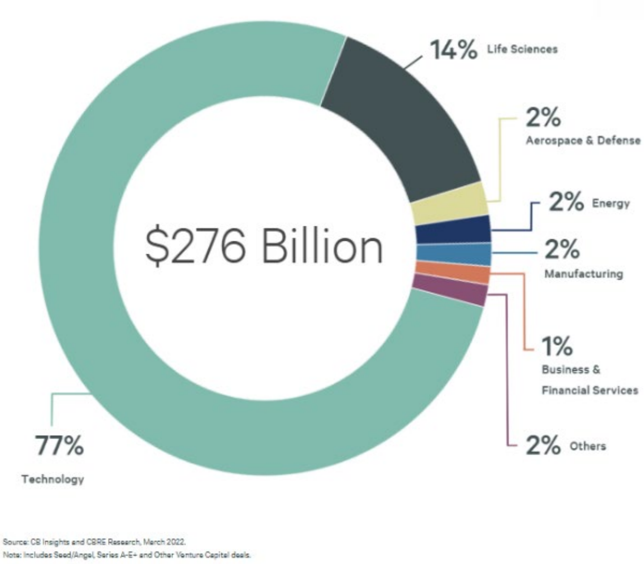
[47] Industry Site Visit, April 4, 2025.
[48] U.S. Department of Defense, *Securing Defense-Critical Supply Chains*, 65.
[49] Jennifer Stewart, Chris Sax, Michael Seeds, Lorenzo Williams, Jack Little, Anthony Borda, Alec Friend, and Riley Van Steenburg, *Vital Signs 2025: The Health and Readiness of the Defense Industrial Base* (Arlington, VA: National Defense Industrial Association, February 2025), 18, https://www.ndia.org/policy/publications/vital-signs. Additionally, FAR 15.404-4 and DFARS 215.404-71 place statutory limits on the allowable profit in accordance with 10 US Code 3322.
[50] "DFARS 215.404-71-2 Performance Risk," *Acquisition.gov*, accessed May 1, 2025, https://www.acquisition.gov/dfars/215.404-71-2-performance-risk.
[51] NCDMM, *Additive Manufacturing Technology Roadmap for Casting and Forging*, 20.
[52] Industry Site Visit, February 27, 2025.

quality and waste challenges plague traditional processes. Current industry estimates indicate that manufacturing defects cost between $32.0-$58.6 billion annually, with approximately 15% of steel mill products becoming scrap during processing.[53]

The DoD identified adoption of AM technologies as a key enabler in the 2023 National Defense Industrial Strategy, stating "DoD will expand efforts to incentivize, invest in, and otherwise promote the use of advanced automation technologies by defense suppliers to reduce total life cycle costs and increase readiness, and, as appropriate, to fill workforce gaps."[54] The Department of Commerce (DOC) and the DoD must partner to address the capital barriers to adoption to enable the modernization and growth of U.S. manufacturing. AM does not attract significant investment from venture capitalists, due in part to its high upfront capital expenditure costs and long return on investment timeframe.[55]

Figure 2: U.S. Venture Capital Funding by Industry Sector, 2021



[53] Thomas, *Annual Report on the U.S. Manufacturing Economy: 2024*, 25.

[54] U.S. Department of Defense, National Defense Industrial Strategy (Washington, DC: Office of the Assistant Secretary of Defense for Industrial Base Policy, January 2024), 20, https://www.businessdefense.gov/NDIS.html.

[55] Colin Yasukochi and Lukas Ault, "Tech Insights: U.S. Venture Capital Funding Sets Record in 2021," *CBRE*, March 15, 2022, https://www.cbre.com/insights/briefs/us-venture-capital-funding-sets-record-in-2021. This is also the source of the chart.

Supply Chain

The global AM supply chain plays a vital role in enabling the full spectrum of AM technologies and shaping strategic advantage. Today's global supply chain landscape is characterized by geographic concentration of critical resources, dependence on global inputs, and vulnerability to geopolitical shocks, prompting the United States to reassess resilience, autonomy, and innovation strategy in this domain.

The global AM supply chain consists of several interdependent stages: the extraction and refinement of critical raw materials; component and subcomponent fabrication; final assembly; and ongoing sustainment and logistics. At each stage, inputs are increasingly digitized and specialized, requiring skilled labor, proprietary software, and protected intellectual property (IP).

Raw materials such as rare earth elements, titanium alloys, high-purity silicon, carbon fiber composites, and specialty polymers are foundational to this chain. China, for example, dominates the processing of rare earth elements, while the Democratic Republic of Congo and Australia are pivotal for cobalt and lithium production.[56] Semiconductor-grade silicon, essential to electronics manufacturing, remains heavily reliant on refining capacity concentrated in East Asia. Production hubs are geographically clustered: Taiwan, South Korea, and Japan lead in semiconductor fabrication; Germany excels in precision manufacturing; and the United States retains leadership in aerospace, biomedical devices, and defense production. Emerging manufacturing nodes, like Mexico and Southeast Asia, are increasingly integrated through "friend-shoring" strategies aimed at reducing reliance on China.[57]

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[56] U.S. Geological Survey, *Mineral Commodity Summaries 2023*, Washington, DC: U.S. Department of the Interior, 2023, https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf

[57] World Economic Forum, Supply Chain Collaboration through Advanced Manufacturing Technologies, October 2019,https://www3.weforum.org/docs/WEF_Supply_Chain_Collaboration_through_Advanced_Manufacturing_Technologies_Report.pdf.

The U.S. AM supply chain is defined by decentralized innovation, public-private partnerships (PPP), and defense-industrial integration. National initiatives such as the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act, the National Strategy for AM, and AM Forward are central to U.S. efforts to re-shore semiconductor production, accelerate digital twin adoption, and expand the footprint and capability of SMM.[58] The DoD actively supports industrial resilience through the Defense Production Act and Industrial Base Analysis and Sustainment programs.[59] Despite its strengths in R&D, skilled labor, and venture capital,[60] the U.S. suffers from overreliance on foreign raw materials, gaps in workforce readiness, and fragmented cybersecurity enforcement.[61]

Resource concentration and geopolitical risk present significant challenges to the global AM supply chain. The dominance of a few countries, particularly China, in the extraction and processing of critical raw materials creates strategic vulnerabilities. Disruptions caused by export controls, trade wars, or political instability can cascade through multiple industries, impacting production timelines and national security. Dependence on concentrated sources undermines supply chain resilience and limits the U.S.'s ability to pivot during crises. Mitigating these risks requires diversification of sourcing, investment in domestic production, and international partnerships to reduce exposure to coercive economic tactics and supply shocks.

Technological bottlenecks in the AM supply chain arise from limited access to specialized equipment, proprietary processes, and high-end capabilities, such as semiconductor lithography or

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[58] National Science and Technology Council, *National Strategy for Advanced Manufacturing*.

[59] U.S. Department of Defense, Industrial Capabilities Report to Congress, Washington, DC: Department of Defense, 2022, https://www.businessdefense.gov/docs/resources/FY2021-Industrial-Capabilities-Report-to-Congress.pdf.

[60] McKinsey & Company, *Building a More Competitive U.S. Manufacturing Sector*, New York: McKinsey Global Institute, 2021, https://www.mckinsey.com/featured-insights/americas/building-a-more-competitive-us-manufacturing-sector.

[61] Luke A. Nicastro, *FY2024 NDAA: Defense Industrial Base Policy*, Congressional Research Service, Insight Report IN12221, January 8, 2024, https://crsreports.congress.gov/product/pdf/IN/IN12221.

advanced materials synthesis. These constraints hinder production scalability, delay innovation, and expose the U.S. to strategic dependencies on foreign suppliers. Addressing these bottlenecks requires sustained R&D investment, public-private collaboration, and strategic partnerships to develop and secure key technologies.[62]

Fragmented policy and coordination across national and institutional boundaries hinder the efficiency and resilience of AM supply chains. Inconsistent standards, regulatory misalignment, and uneven technology readiness create barriers to interoperability, delay technology deployment, and complicate crisis response. This fragmentation is especially problematic among allied nations seeking to synchronize industrial strategies. Overcoming these challenges requires harmonized regulations, shared digital infrastructure, and multilateral frameworks to align incentives, streamline collaboration, and enhance collective industrial agility.

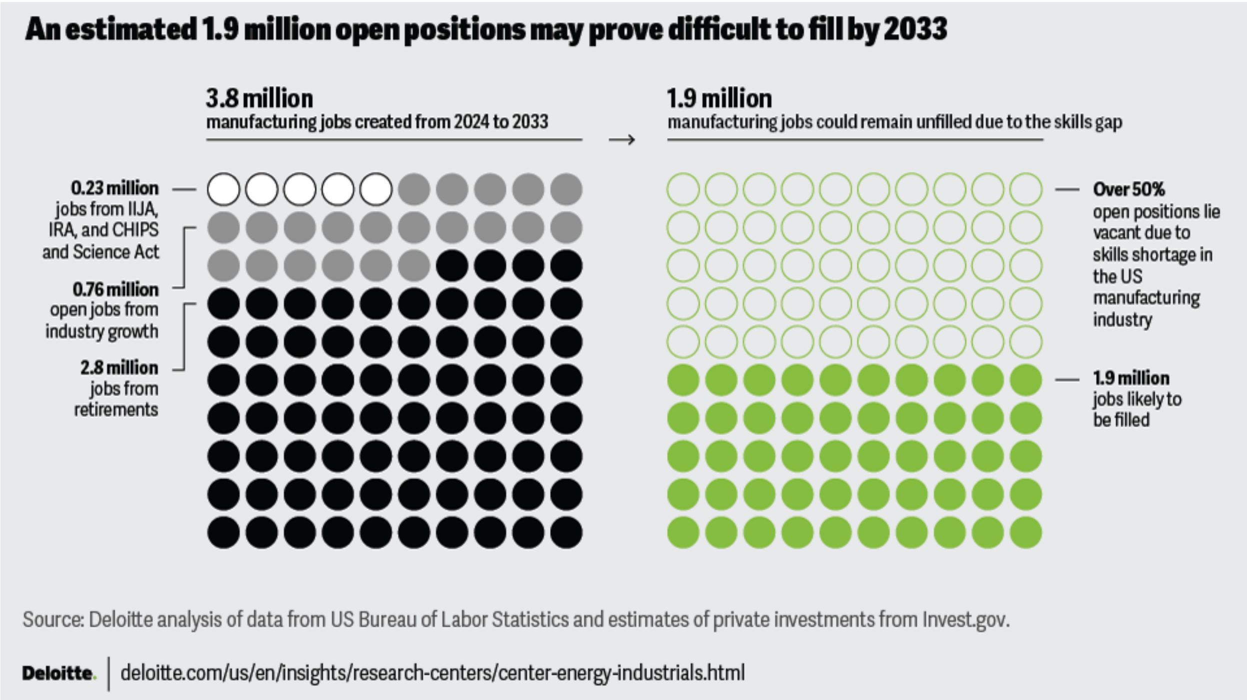
Workforce

The barriers to AM technology adoption and supply chain challenges are exacerbated by the U.S.'s manufacturing workforce shortage. As previously mentioned, the current manufacturing workforce is at its lowest total since before WWII. The outsourcing of jobs to overseas competitors, the lack of domestic investment, and the cumulative effect of decades of college education primacy have created a stagnant industry without an established workforce pipeline. The push towards college education for everyone during the 1980s significantly degraded the nation's vocational training system. The difference in academic rigor, time commitment, and financial cost precluded replacing one path with the other for many potential tradesmen. Students who would have previously pursued vocational training joined the ranks of unskilled laborers instead.[63]

[62] National Science Foundation, Engineering Research Centers Program Overview, Alexandria, VA: NSF, 2022, https://www.nsf.gov/eng/engineering-research-centers.

[63] Adler and Bonvillian, "America's Advanced Manufacturing Problem."

Estimates based on U.S. Bureau of Labor data predict the nation will create 3.8 million new manufacturing jobs by 2033, but 1.9 million of them will go unfilled due to workforce shortages.[64]



While past industry-specific decisions have contributed to the shortage, there are larger demographic issues compounding the problem today. One trend is especially challenging: the U.S. population is aging and is below a replacement-level birthrate. As of 2024, the total fertility rate is 1.8 births per woman (replacement value is 2.1) with a median age of 38.9 in the U.S.[65] If that trend continues, the over-65 population growth will outpace the critical 25-54 demographic which

[64] John Coykendall, Kate Hardin, John Morehouse, Victor Reyes, and Gardner Carrick. "Strong Growth in US Manufacturing, even as Talent Challenges Persist." *Deloitte Research Center for Energy & Industrials*, April 3, 2024. https://www2.deloitte.com/us/en/insights/industry/manufacturing/supporting-us-manufacturing-growth-amid-workforce-challenges.html. This is also the source for the graphic projecting job vacancies.

[65] US Census Bureau, "America Is Getting Older," *Census.gov*, June 22, 2023, accessed April 20, 2025, https://www.census.gov/newsroom/press-releases/2023/population-estimates-characteristics.html; Central Intelligence Agency, "Total Fertility Rate," *The World Factbook*, accessed April 20, 2025, https://www.cia.gov/the-world-factbook/field/total-fertility-rate/.

traditionally comprises the bulk of the workforce.[66] Furthermore, a recent Cato Institute poll found that only 14% of Generation Z would consider an industrial career.[67]

Another overarching demographic challenge is the unwillingness of younger generations to relocate for work. Americans are no longer as migratory as previous generations. Sixty percent of young adults live within 10 miles of where they were born, while 80% live within 100 miles. "Even the prospect of higher earnings in more distant locations does little to change these patterns."[68] This means that the workforce in the immediate vicinity is most likely the only human capital available to support manufacturing initiatives.

All these factors indicate the workforce shortage will get worse in the future, but its present-day impacts are already cause for concern. According to a 2024 survey by the National Association of Manufacturers, over 65% of respondents listed recruitment and retention of talent as their primary business concern.[69] Promote-from-within programs are a common approach to workforce management among SMM due to the difficulty of finding employees. If an employee demonstrates interest and aptitude in an entry-level position, companies will provide upskilling opportunities and increased responsibilities. One company paid employees a bonus for referring a friend or family member if they were hired.[70]

The increasing demand for capable workers is opening opportunities for unskilled workers to obtain certifications and increased marketability. One ADMAN manager highlighted that one

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[66] Congressional Budget Office, *The Demographic Outlook: 2024 to 2054* (Washington, DC: Congressional Budget Office, January 18, 2024), https://www.cbo.gov/publication/59899.

[67] Emma Burleigh, "Nearly 4 Million New Manufacturing Jobs Are Coming to America as Boomers Retire—but It's the One Trade Job Gen Z Doesn't Want," *Fortune*, April 17, 2025, accessed April 20, 2025, https://fortune.com/article/us-manufacturing-jobs-gen-z-baby-boomers-retirement-immigration/.

[68] Nathaniel Hendren, Sonya R. Porter, and Ben Sprung-Keyser, "New Data Tool and Research Show Where People Move as Young Adults," *United States Census Bureau*, July 25, 2022, https://www.census.gov/library/stories/2022/07/theres-no-place-like-home.html.

[69] Coykendall, Hardin, et al, "Talent Challenges Persist."

[70] Industry Site Visit, April 8, 2025.

of his best workers was a former waitress who had no technical experience but was skilled at keeping track of multiple orders started at different times and where each was in the production process.[71] With the average annual earnings for manufacturing employees at $102,629, reskilling programs could provide an immediate injection of human capital to the industrial base and provide the potential for upward mobility to an increasingly disenfranchised portion of the population.[72]

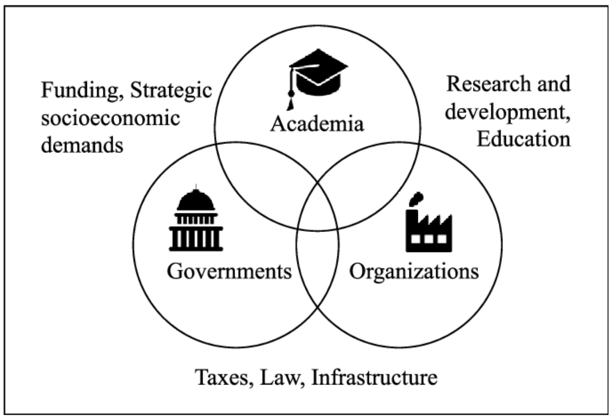
Industrial Policy

The current approach to resuscitating the U.S. industrial base depends on a concept called the Triple Helix. Although cooperation between industry, academia, and government existed previously, the concept was named and formalized in 1995 by sociologists Henry Etzkowitz and Loet Leydesdorff. According to their groundbreaking paradigm, any successful national innovation system requires the integration of academic, industry, and government organizations working in collaboration through a spiral process of recurring, mutually supporting exchanges of information and resources.[73] In the U.S., this partnership takes the form of universities, corporations, and federal government stakeholders like the DoD or the Department of Energy (DOE).

While the theory is credited with helping to advance fields as diverse as rocketry, stealth, and synthetic materials (among others), there are several drawbacks to the approach. First, the federal government pays a disproportionate percentage of the cost by providing funding to both the academic and industry partners. This is due to the lack of incentive for businesses to invest in long-lead time, speculative research. In a constrained fiscal environment, scarce dollars can

[71] Industry Site Visit, January 16, 2025.
[72] National Association of Manufacturers, "Manufacturing in the United States," *nam.org*, April 2025, https://nam.org/mfgdata/.
[73] Henry Etzkowitz and Loet Leydesdorff, "The Triple Helix: University–Industry–Government Relations. A Laboratory for Knowledge-Based Economic Development," EASST Review 14, no. 1 (January 1995): 14–19, https://ssrn.com/abstract=2480085.

become a chokepoint or death knell for promising capabilities. Second, the approach emphasizes the first stage of innovation (discovery) where the U.S. is strongest and virtually ignores the final stage (production process) that is at the heart of the industrial base challenge.[74] The focus on discovery also makes it a long process that may require years, if not decades, to produce results. Third, it takes a top-down approach, with only a limited number of players with access to the resources required to make progress. And finally, the Triple Helix does not adequately address workforce needs. Because the approach is focused on producing new technology, there is an over-emphasis on doctoral-level higher education with little consideration given to the majority of workforce needs which exist below that top tier.[75]



Despite these shortcomings, the approach does produce positive returns. For example, by including photonic integrated circuits and other optoelectronic devices in the scope of "semiconductors" incentives, the CHIPS Act explicitly aims to strengthen domestic capacity in photonics manufacturing alongside electronics. The Act's funding and tax credits have sparked substantial private-sector investment, with companies in the semiconductor ecosystem announcing over 100 projects across 28 states, totaling more than half a trillion dollars in private investment.[76]

[74] Dan Breznitz, *Innovation in Real Places: Strategies for Prosperity in an Unforgiving World*, Oxford: Oxford University Press, 2021.

[75] Rafaela Garbelini Anuardo, Maximilian Espuny, Ana Carolina Costa, and Otávio Oliveira, "Toward a Cleaner and more Sustainable World: A Framework to Develop and Improve Waste Management through Organizations, Governments and Academia," *Heliyon* 8 (2022), DOI: 10.1016/j.heliyon.2022.e09225. This citation refers to the source of the Triple Helix graphic, not the text.

[76] "Semiconductor Supply Chain Investments," *Semiconductor Industry Association*, accessed April 29, 2025, https://www.semiconductors.org/chip-supply-chain-investments/; ICYMI: 'The CHIPS Act Has Already Sparked $200 Billion in Private Investments for U.S. Semiconductor Production,'" The American Presidency Project, accessed April 29, 2025, https://www.presidency.ucsb.edu/documents/icymi-the-chips-act-has-already-sparked-200-billion-private-investments-for-us.

According to the Semiconductor Industry Association, these projects create and support over 500,000 American jobs.[77]

Another policy in 2022, the Inflation Reduction Act (IRA), while primarily focusing on energy and climate, contains strong advanced manufacturing incentives. The IRA established production credits for U.S.-made renewable energy components, batteries, and electric vehicles, motivating over $92 billion in new factory investments in high-tech manufacturing and an estimated 85,000 new jobs.[78] Complementing these legislative and strategic efforts is the Manufacturing USA program (See Appendix C: Stakeholders). This initiative, launched in 2014, established a network of AM institutes to bring together government, industry, and academia for pre-competitive R&D and workforce development in specific technology domains.[79]

Global Perspective

The U.S. is not alone in recognizing the potential benefits of AM. Just as the Asian Tigers sought to undermine American manufacturing dominance in the last century, competitors like China are not sitting idly by while the U.S. attempts to reclaim its manufacturing prowess. As the unipolar world of U.S. hegemony shifts back towards a multi-polar landscape dominated by competition and nationalistic agendas, industrial nations are engaging in an economic arms race to control supply chains, market shares, and international standards. In this fractious environment, even allied capabilities and policies bear consideration. The following section will evaluate China

[77] "Semiconductor Supply Chain Investments."

[78] "U.S. Department of the Treasury Releases Guidance on Domestic Content Bonus for Clean Energy Credits," *U.S. Department of the Treasury*, February 8, 2025, https://home.treasury.gov/news/press-releases/jy2788; Leo Banks, "How Inflation Reduction Act Electric Vehicle Incentives Are Driving a U.S. Manufacturing Renaissance," *Center for American Progress*, November 22, 2023, https://www.americanprogress.org/article/how-inflation-reduction-act-electric-vehicle-incentives-are-driving-a-u-s-manufacturing-renaissance/.

[79] Industry Site Visit, January 16, 2025.

(the pacing challenge), Russia (a nation mobilized for war), and France (an ally) across the four critical themes: technology, supply chain security, workforce development, and industrial policy to better inform U.S. AM strategy development.[80]

China

China is making substantial progress in the AM sector as part of a strategic effort to position itself as a global leader in high-technology industries.[81] In 2015, China released its state-led industrial policy, Made in China 2025, which aims to "transform China into a global leader in AM by 2025."[82] Made in China 2025 is a strategic 10-year plan that lays out a roadmap for China to not only enhance innovation but also improve productivity along 10 key strategic sectors to reduce China's reliance on foreign technology imports.[83] China has made significant strides to foster innovation, as highlighted by its establishment of National Manufacturing Innovation Centers (MICs). In response to the U.S.'s Manufacturing USA and Germany's Industry 4.0, China has established 33 MICs with the goal of establishing 40 by 2025.[84] The MICs are strategically focused on developing technologies surrounding 10 industry sectors with the intent to create industrial and academic ecosystems that drive innovation and accelerate product development.[85] Additionally, to

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[80] The analysis of China and Russia is informed by publicly available secondary sources only as site visits and interviews were impractical for obvious reasons.

[81] Outside analysis of Chinese economic performance is increasingly difficult due to the Chinese Communist Party's policy of restricting the release of data since 2015.

[82] Camille Boullenois, Malcolm Black, and Daniel H. Rosen, *"Was Made in China 2025 Successful?"* Rhodium Group, May 2025, accessed May 7, 2025, https://rhg.com/research/was-made-in-china-2025-successful/.

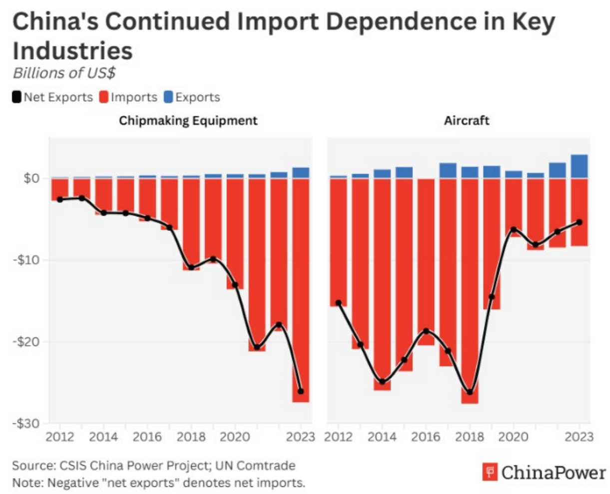
[83] Institute for Security and Development Policy. *Made in China 2025 BACKGROUNDER*. June 2018. Accessed May 7, 2025. https://www.isdp.eu/wp-content/uploads/2018/06/Made-in-China-Backgrounder.pdf.

[84] Michael Molnar, Kelley Rogers, Frank Gayle, Susan Ipri-Brown, Mai Tran, Joseph Long, Clifton Ray, Albert Shih, and Douglas Thomas, *China's Manufacturing Innovation Centers: A Benchmarking Report for the Manufacturing USA Network*, NIST Advanced Manufacturing Series (NIST AMS 600-17), National Institute of Standards and Technology, May 2025, accessed May 9, 2025, https://doi.org/10.6028/NIST.AMS.600-17.

[85] Molnar et al., *China's Manufacturing Innovation Centers*, 5.

accelerate manufacturing development and the adoption of emerging AM technologies, China has enacted preferential tax policies to promote industrial growth and technological innovation.[86]

Technology (China)



China has made considerable investments in its infrastructure to demonstrate its commitment to becoming a global leader in AM. China is investing heavily in innovative infrastructure, as previously mentioned in its innovation centers, as well as making significant investments in its information infrastructure, where it is prioritizing projects that support its advancement of 5G, IoT, AI, data centers, and other technologies aligned with its Made in China strategy.[87] Despite massive investment, China still faces critical limitations. Its domestic photonics industry remains dependent on foreign IP and core components, particularly in high-end laser diodes, optical materials, and extreme ultraviolet (EUV) lithography systems.[88] Chinese firms such as Shanghai Micro Electronics Equipment are attempting to develop domestic alternatives to foreign EUV lithography tools, although they remain years behind global leaders.[89] U.S. export controls, tariffs, and entity listings (e.g. Huawei)

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[86] Arendse Huld, "China's Tax Incentives for the Manufacturing Sector in 2023," *China Briefing*, August 14, 2023, accessed May 7, 2025, https://www.china-briefing.com/news/china-preferential-tax-policies-for-manufacturing-sector/.

[87] Dorcas Wong, "How Can Foreign Technology Investors Benefit from China's New Infrastructure Plan?," *China Briefing*, August 2020, accessed May 7, 2025, https://www.china-briefing.com/news/how-foreign-technology-investors-benefit-from-chinas-new-infrastructure-plan/.

[88] China Power Team, "Measuring China's Manufacturing Might." This citation is for the graph, not text.

[89] Peter Engelke and Emily Weinstein, "Assessing China's Approach to Technological competition with US," Atlantic Council Strategic Insights Memo, April 24, 2023, https://www.atlanticcouncil.org/content-series/strategic-insights-memos/assessing-chinas-approach-to-technological-competition-with-the-united-states/.

are aimed at slowing China's ascent in advanced technologies.[90] These actions have prompted countermeasures and a push for "de-Americanization" of Chinese supply chains.

Supply Chain (China)

Critical to advancing the Made in China 2025 strategy is building resilient, redundant, and diverse supply chains. China has a key advantage in this pursuit as it dominates the rare earth minerals, which are invaluable components for producing high-end technology. China has overwhelming control of rare earth minerals as it currently partners with other nations to produce 60% of the raw materials and processes 85% of the global output.[91] China's lax environmental policies, coupled with the low cost of labor, allowed China to rapidly build its dominance and exert control over the rare earth sector. This dominance affords China significant geopolitical and economic leverage, enabling it to exert considerable influence over global supply chains and strategic manufacturing sectors.

Another way China is building resilience in its supply chain is through its digital smart supply chain initiatives. China's investments in advanced technologies such as AI and IoT have also helped it build a more resilient supply chain as it transforms its supply chain network to become more efficient, transparent, and responsive.[92] Furthermore, the Chinese government does not have qualification or regulatory concerns about using 3-D printed parts. In 2022, Tsinghua

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[90] Dan Ward and Matt MacGregor, "Arming the Eagle, Outpacing the Dragon: Understanding and Out Competing China's Defense Acquisition and Innovation System," MITRE, June 17, 2022, https://www.mitre.org/news-insights/publication/arming-eagle-outpacing-dragon-understanding-and-out-competing-chinas.

[91] John Zadeh, "China's Rare Earth Export Strategy: Global Supply Risks and Diversification Efforts," *Discovery Alert*, May 2, 2025, accessed May 9, 2025, https://discoveryalert.com.au/news/chinas-rare-earth-export-strategy-global-supply-2025/.

[92] Tianyi Xiao, "China's Supply Chain Transformation: Technological Innovations and Future Outlook," *China Briefing*, January 7, 2025, accessed May 7, 2025, https://www.china-briefing.com/news/chinas-supply-chain-transformation-technological-innovations-and-future-outlook/.

University of China began the construction of a 180-meter-tall 3D-printed dam on the Tibetan Plateau. If completed, the Yangqu Dam will be the largest robotic 3D-printed structure.[93]

Workforce (China)

China possesses a substantial skilled labor force, with approximately 20% of its workforce employed in the manufacturing sector.[94] While a significant share of these positions is concentrated in traditional industries such as garment production and consumer electronics assembly, relatively few workers are engaged in high-technology fields.[95] However, China is confronting demographic pressures stemming from a declining and aging labor population. Compounding this challenge, the country's strategic investments under the Made in China 2025 initiative, particularly in smart manufacturing, have exacerbated skills mismatches, highlighting a growing gap between workforce capabilities and the demands of AM technologies.[96]

To address these challenges, China is actively pursuing vocational education reforms and reskilling initiatives aimed at aligning its workforce with the evolving demands of AM. China's Ministry of Education has introduced more than 40 new vocational programs, with over half of them concentrated on AM and digital technologies. Additionally, China's 5-year plan 2021-2025 recognized these issues and dedicated significant funding for reskilling and upskilling programs to develop workers to address their AM initiatives.[97]

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[93] Christina Petridou, "AI and 3D Printers Build 180-Meter-Tall Dam on Tibetan Plateau," May 18, 2022, https://www.designboom.com/design/ai-3d-printing-build-180-meter-tall-dam-tibetan-plateau-05-18-2022/.

[94] Lin Xiaozhao, "Almost 20% of China's Workforce Is in Manufacturing, Study Shows," *Yicai Global*, July 22, 2022, accessed May 7, 2025, https://www.yicaiglobal.com/news/almost-20-of-china-workforce-is-in-manufacturing-study-shows.

[95] Xiaozhao, "Almost 20% of China's Workforce."

[96] Ricky Li and Ian Shine, "The future of jobs in China: the rise of robotics and demographic decline are opening up skills gaps," *World Economic Forum*, April 28, 2025, accessed May 7, 2025, https://www.weforum.org/stories/2025/04/the-future-of-jobs-in-china-the-rise-of-robotics-and-demographic-decline-are-opening-up-skills-gaps.

[97] Li and Shine, "The future of jobs in China."

Industrial Policy (China)

As a fast follower, China has developed its own state-centric adaptation of the Triple Helix model, strategically integrating industry, academia, and government to advance national objectives in the manufacturing and AM sectors. Different from the market-driven system, China's government-led, top-down policies significantly shape and prioritize innovation and product development to align with its Made in China 2025 strategy. Specifically, China's modified triple helix model has created industry education cities to better align resources to address their manufacturing programs.[98]

Russia

Unlike peer competitors who pursue innovation-driven ecosystems, Russia advances through a state-centered, reactive approach in AM. The paucity of data available on Russian manufacturing makes comparative analysis difficult. Far from being an exemplar of advanced manufacturing, Russia, a country currently mobilized for war, serves as a cautionary tale for an unmodernized DIB supporting large-scale combat operations engaged in attrition warfare.

Technology (Russia)

While global leaders in AM increasingly integrate ADMAN, robotics, and industrial AI to drive productivity and innovation, Russia's digital infrastructure lags both in scale and sophistication. Contributing less than 0.4% of global AM output, Russia remains a strategic adopter rather than a first mover.[99] Though the Kremlin has sponsored initiatives to digitalize production, particularly in optics, biotech, and automation, the ecosystem is hampered by

98 Chen Cheng and Si Cheng, "The Triple Helix Model for Industry-Education City Integration in China: A Development Approach," *SAGE Open* 14, no. 2 (May 2024): 1–15, accessed May 7, 2025, https://journals.sagepub.com/doi/full/10.1177/21582440241250111.

99 Yuri Simachev, Anna A. Fedyunina, and Nikolay Gorodny, "Global Advanced Manufacturing Markets — A New Opportunity for Russia's Technological Upgrade," *Journal of the New Economic Association* 53, no. 1 (2022): 202–212, https://doi.org/10.31737/2221-2264-2022-53-1-10.

persistent dependency on foreign technologies. The country's approach reflects a pattern of reverse engineering and selective assimilation, as opposed to building robust, indigenous capabilities. Russia's capacity to direct global technology development is limited by both the lack of scalable homegrown platforms and insufficient private-sector research investment.

RUSSIAN IMPROVISATION

Russia remains heavily dependent on foreign suppliers for semiconductors and has adopted increasingly improvised methods to circumvent international sanctions. In 2022, credible reports indicated that Russian forces extracted microchips from captured consumer appliances and civilian vehicles.[100100] Since then, analysts have documented large-scale imports of Western consumer goods into Russia via third-party countries up through at least mid-2024. U.S. and U.K. intelligence assessments have concluded that embedded microchips in these goods are being repurposed for use in Russian tanks, drones, and missiles.[101101]

Supply Chain (Russia)

Russia's manufacturing supply chain strategy has become increasingly insular in response to sanctions, trade restrictions, and global realignments. Unlike peer economies that pursue resilience through diversification and redundancy, Russia's model leans heavily on import substitution and state stockpiling. Sanctions restrict Russia's access to advanced software, precision manufacturing equipment, and high-performance computing platforms necessary to develop a robust digital thread infrastructure.[102] Import substitution efforts have partially

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[100] U.S. Senate Committee on Appropriations, *A Review of the President's Fiscal Year 2023 Funding Request for the Department of Commerce*, video of hearing, 1:45:29, April 27, 2022, U.S. Senate Appropriations Committee, 25:50–26:15, https://www.appropriations.senate.gov/hearings/a-review-of-the-presidents-fiscal-year-2023-funding-request-for-the-department-of-commerce.

[101] U.S. Senate Committee on Homeland Security and Governmental Affairs, Hearing Record Documents, February 27, 2024, https://www.hsgac.senate.gov/wp-content/uploads/2024-02-27-Hearing-Record-Documents.pdf; U.S. Senate Committee on Homeland Security and Governmental Affairs, PSI Staff Memo to Members on Sanctions Hearing, February 21, 2024, https://www.hsgac.senate.gov/wp-content/uploads/2024.2.21-PSI-Staff-Memo-to-Members-on-Sanctions-Hearing.pdf.

[102] Mathieu Boulègue, Justin Bronk, Karolina Hird, Jaclyn Kerr, Rob Lee, and Michael B. Petersen, "Assessing Russian Plans for Military Regeneration," Chatham House, July 9, 2024, DOI: 10.55317/9781784136178,

succeeded in basic metals and electronic components, but persistent gaps remain in semiconductors, composites, and advanced materials essential for next-generation platforms.[103] Moscow has prioritized domestic component production in critical sectors such as aerospace and microelectronics, but the state-centered system leads to operational bottlenecks while failing to effectively integrate into worldwide supply networks. Russia's strategic shift away from global partnerships leads to its isolation from international innovation networks essential for design breakthroughs and scalable production materials. This strategy could ultimately widen the technology gap rather than narrow it.

Workforce (Russia)

Workforce agility and deep technical expertise are essential elements for maintaining global competitiveness in manufacturing. Russia employs centralized control combined with specific reforms for labor strategy yet continues to face productivity shortfalls due to unresolved structural issues. Russia implemented changes to its vocational and engineering education system to better meet the requirements of its industrial sectors. Overall, sector productivity continues to fall short of Organization for Economic Co-operation and Development levels by reaching only one-third to one-half of comparable benchmarks.[104] This shortfall is rooted in a theoretical orientation to education, limited experiential training, and demographic headwinds, but it is exacerbated by the ongoing war with Ukraine which is siphoning a significant portion of the working age population into the military. The British Broadcasting Corporation estimates 40% of

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[103] Boulègue et al. *Assessing Russian Plans for Military Regeneration.*

[104] New Development Bank, "Program of Development of Educational Infrastructure for Highly Skilled Workforce," accessed May 7, 2025, https://www.ndb.int/project/russia-development-educational-infrastructure-highly-skilled-workforce/.

Russia's casualties are soldiers who had no military affiliation before the war started.[105] With a shrinking working-age population, Russia's industrial ambitions are increasingly constrained by talent shortages and limited geographic mobility. Russia is heading toward a phenomenon known as "reverse industrialization," where the manufacturing industry switches from high-tech jobs to more labor-intensive forms of work, and its lack of a labor force is a major contributing factor.[106] These human capital challenges diminish the scalability of advanced manufacturing within the country.

Industrial Policy (Russia)

The Triple Helix model is a cornerstone of global innovation ecosystems, but in Russia, this integrative model is underdeveloped. While the state has launched programs in nanotechnology and digital engineering, bureaucratic silos, legacy command structures, and an underpowered entrepreneurial base undermine execution. Russia's top-down governance structure restricts decentralized collaborative processes that drive innovation in the U.S., Germany, and South Korea.[107] Moreover, private industry often lacks the incentives or autonomy to drive commercialization, leaving public research stranded in the laboratory. Russia's AM ecosystem

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[105] Peter Felstead, "Russian Death Toll in Ukraine War Has Passed 50,000 According to BBC/Mediazona Analysis," *European Security and Defense*, April 18, 2024, https://euro-sd.com/2024/04/major-news/37694/russian-death-toll-in-ukraine/. This is also the source of the chart.

[106] Hlib Parfonov, "Russia Experiences Reverse Industrialization as Economy Deteriorates," *Eurasia Daily Monitor* 22 (March 4, 2025), accessed April 19, 2025, https://jamestown.org/program/russia-experiences-reverse-industrialization-as-economy-deteriorates/.

[107] Harley Balzer and Jon Askonas, "The Triple Helix after Communism: Russia and China Compared," *Triple Helix* 3, no. 1 (January 21, 2016): 1–28, https://doi.org/10.1186/s40604-015-0031-4.

struggles to translate research into scaled production capabilities without a systemic bridge between discovery and deployment.

France

France is currently undertaking a revitalization of the French economy through the transformation of its industrial sectors. France 2030 was launched in October 2021 with the goal of enabling a sustainable transition of the French economy in the automotive, aerospace, digital, green industry, biotechnology, culture, and healthcare industries by 2030.[108] France 2030 identifies 10 key objectives, most of which require AM to achieve.[109] These objectives are all shaped by France's high regulatory environment, which requires sustainable and clean manufacturing. Despite these restrictions, manufacturing is the most important sector of the French economy, accounting for 9.7% of GDP.[110]

Technology (France)

The number of European Union (EU) firms using AM increased dramatically from 2009 to 2023, growing 130%.[111] French AM is most advanced within the ADMAN sector, which was estimated at $2 billion in 2023, 30% of the ADMAN market in the EU, and 11% of the global market. The ADMAN market is expected to grow 8% over the next few years.[112] The main applications for ADMAN in France are the aerospace, defense, and space sectors. Due to the EU's

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[108] Aloïs Kirchner, "Zooming In On French Industrial Policy," *Institut Montaigne*, October 3, 2022, accessed May 7, 2025, https://www.institutmontaigne.org/en/expressions/zooming-french-industrial-policy.

[109] Government of France, "Major Objectives - France 2030," *info.gouv.fr*, accessed May 7, 2025, https://www.info.gouv.fr/grand-dossier/france-2030-en/major-objectives.

[110] "Trading Economics," accessed May 7, 2025, https://tradingeconomics.com/.

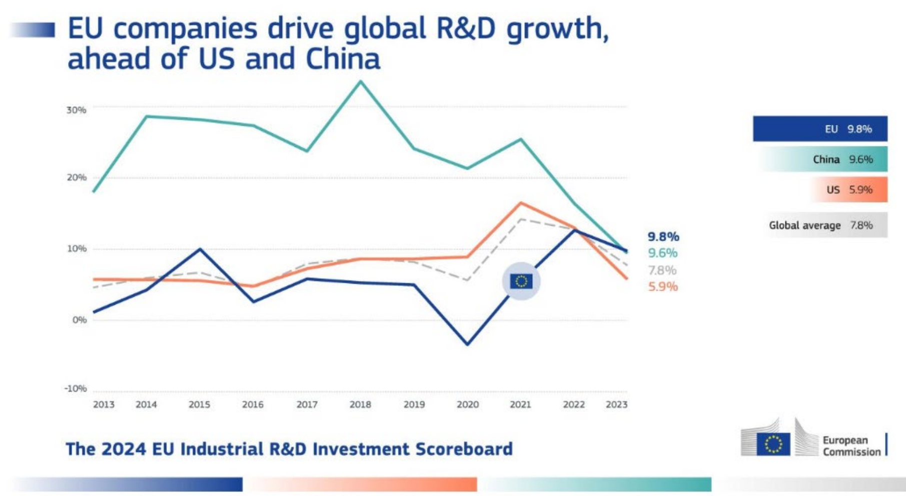
[111] Josefina Fabiani, Jorge Soguero Escuer, Elisa Calza, Cesare Dunker, and Giuditta De Prato, *Strategic Insights into the EU's Advanced Manufacturing Industry: Trends and Comparative Analysis* (Luxembourg: Publications Office of the European Union, 2024), 13, https://doi.org/10.2760/7959469.

[112] U.S. Commercial Service, *France Additive Manufacturing Market* (U.S. Embassy Paris: U.S. Commercial Service, United States Department of Commerce, 2024), https://www.trade.gov/market-intelligence/france-additive-manufacturing-market.

high regulatory requirements for sustainability, the French ADMAN industry specifically focuses on developing products using bio-based, recycled, and biodegradable materials.[113]

Supply Chain (France)

France is a small country compared to the U.S. and China, putting additional strain on its supply chains. Critical sectors try to maintain domestic supply chains, but due to the size of the country, this is challenging and often results in highly integrated supplier networks. Therefore, many French companies look across the EU and to allies like the U.S. to add redundancy to supply chains.[114] The EU consistently invests heavily in R&D, with initiatives like Horizon Europe (2021–2027), with the goal of bringing new technologies to supply chains.[115]



Global research and development growth of EU companies ahead of China and US

Despite these investments, French and more broadly, EU, supply chain resilience faces notable risks.[116] A heavy reliance on foreign suppliers for critical raw materials, such as rare earth

[113] U.S. Commercial Service, *France Additive Manufacturing Market*.
[114] Thierry Dubois, "French Supply Chain Struggles To Keep Up With Production Needs," *Aviation Week Network*, May 2, 2023, accessed May 7, 2025, https://aviationweek.com/aerospace/manufacturing-supply-chain/french-supply-chain-struggles-keep-production-needs.
[115] European Commission, *Horizon Europe: The EU Research and Innovation Programme 2021–2027* (Brussels: European Commission, 2021), https://op.europa.eu/s/z5m7.
[116] The Joint Research Centre: EU Science Hub, “EU companies lead global R&D investment growth, breaking decade-long trend,” *European Commission*, December 18, 2024, https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/eu-companies-lead-global-rd-investment-growth-breaking-decade-long-trend-2024-12-18_en. This is the source for the R&D growth chart.

elements, lithium, and advanced semiconductors, has created significant vulnerabilities.[117] Strategic sectors depend on imports from China, the U.S., and other non-EU countries, exposing European manufacturing to geopolitical tensions and global supply disruptions. In response, the EU has adopted risk mitigation strategies, including the European Raw Materials Alliance and the European Chips Act, to secure domestic capacities and diversify sourcing.[118]

Workforce (France)

Between 1995 and 2017, France experienced a loss of 900,000 manufacturing jobs, a 27% decrease.[119] France now finds itself in a similar position to the U.S., trying to build back strategic manufacturing industries and find workers to fill critical positions. In 2019, a manufacturing hub in France had 18,000 unfilled jobs.[120] Employers cited the potential employees' lack of computer and digital skills to run production lines as the main driver for the unfilled positions.[121] In a 2023 survey, 61% of employers, especially SMM, identified skill shortages as a primary cause of the lack of suitable labor.[122] The youth education system in France contributes to this problem. At the age of 15, French students track into vocational, technical, or general high schools.[123] The primary

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[117] European Commission, *Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability*, COM(2020) 474 final (Brussels: European Commission, September 3, 2020), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474.

[118] European Commission, *A Chips Act for Europe*, Brussels: European Commission, 2022, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/european-chips-act_en;
McKinsey & Company, *Reimagining European Industry for a Sustainable Future*, New York: McKinsey & Company, 2023, https://www.mckinsey.com/capabilities/sustainability/our-insights/reimagining-industrial-operations.

[119] *Les Thémas de la DGE*. Paris: Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, Direction générale des Entreprises, May 20, 2024. Accessed May 7, 2025. https://www.entreprises.gouv.fr/files/files/Publications/2024/themas/Themas-DGE-N20-VE.pdf.

[120] Liz Alderman, "In an Industrial Corner of France, 18,000 Jobs Are On Offer. Why Aren't People Taking Them?," The New York Times, July 27, 2019, Business, https://www.nytimes.com/2019/07/27/business/labor-manufacturing-france.html.

[121] Alderman, "18,000 Jobs Are On Offer."

[122] Banque de France, *Bulletin de la Banque de France*, no. 251/4 (March–April 2024): 1–12, https://www.banque-france.fr/system/files/2024-07/824023_BDF251_4_Phillips_US_EN_Vfinale.pdf.

[123] Eurydice, "France: Overview," *National Education Systems*, last updated April 22, 2025, accessed April 24, 2025, https://eurydice.eacea.ec.europa.eu/national-education-systems/france/overview

goal of the vocational path is to create an active working life for students, but this system also makes it challenging for individuals to change career paths later in life due to early specialization.[124]

Industrial Policy (France)

France does not have a traditional triple helix between government, academia, and industry, like that seen in the U.S., but France does have a strong relationship between these three entities in the form of its robust apprenticeship program. This partnership is trying to address workforce challenges in AM by matching students with work opportunities.[125] Under this program, students as young as 16 can sign an apprenticeship contract and split time between class and an entry-level job under the management of an apprentice supervisor, with the skills learned at work counting towards educational requirements. Apprentices are paid at a reduced rate compared to full-time employees, but they gain valuable work experience while still in school and are often hired as full-time employees with the sponsoring company.[126]

Policy Recommendations

The current global and domestic landscape lends itself to addressing the U.S. manufacturing challenges through two focused sets of policy recommendations. The U.S. federal government, working with state and local governments, must take a whole of government approach to address the country's need to expand domestic AM. The federal government should also take focused actions within the DoD, leveraging current federal investments, to incentivize and fund adoption of AM. By leveraging planned DoD investments, the federal government can drive the

[124] Eurydice, "France: Overview."; Industry Site Visit, April 10, 2025.
[125] Industry Site Visit, April 7, 2025.
[126] Directorate of Legal and Administrative Information (Prime Minister), Ministry of Labour, "Apprenticeship Contract," Service-Public.Fr, March 3, 2025, https://www.service-public.fr/particuliers/vosdroits/F2918.

adoption of AM without dedicating significantly more funding. The following policy recommendations address U.S. challenges across technology, supply chain, workforce, and industrial policy.

	Whole of Government	Department of Defense
Technology	Provide SMM with access to government-furnished, leased AM equipment through direct grants, subsidized leases, and shared-access facilities.	Leverage existing DoD funds to incentivize the adoption of AM technology within the DIB.
Supply Chain	Strengthen U.S. supply chain resilience through public-private partnership and prioritization.	Invest in providing Cybersecurity Maturity Model Certification compliant networks to SMM to grow the DoD supply chain.
Workforce	Expand E3 immigrant visa opportunities for legal immigrants to work in manufacturing jobs.	Revector the mission of the Office of Local Defense Community Cooperation to leverage the 800+ military facilities across the U.S. and align local, state, and federal resources geared toward manufacturing.
Industrial Policy	Renew and expand the Strengthening Community Colleges Training Grants.	

Whole of Government Policy Recommendations

Technology: Provide SMM with access to Government-furnished, Leased AM equipment through direct grants, subsidized leases, and shared-access facilities.

Strategic Rationale

The DIB's health depends on SMM, however these companies lack access to capital for AM technologies that would enable them to compete effectively in an increasingly digitized production environment. An Advanced Manufacturing Equipment Access Program (AMEAP) addresses this critical barrier to technology adoption. This policy draws inspiration from successful historical models such as the WWII machine tool program, which provided critical production equipment to defense contractors. By reducing capital barriers to technology adoption, the program would enable SMM to increase production capacity for defense-critical components.

Implementation

AMEAP would provide SMM with access to advanced manufacturing equipment through a three-tiered approach. First, equipment grants would offer direct financial assistance covering 50-80% of equipment costs for SMM engaged in defense-critical manufacturing, with grant amounts ranging from $250,000-$5 million. Second, subsidized leases would provide government-backed financing with below-market interest rates (2-3% vs. typical 8-12%) and extended terms (7-10 years vs. typical 3-5 years), reflecting the longer time horizons needed for return on investment.[127] A 30% government guarantee on lease values would reduce financial institution risk, creating incentives for private capital participation. Third, shared-access facilities would create "manufacturing commons" where SMM could access advanced equipment on a time-share basis, operated by local Manufacturing Extension Partnership (MEP) centers, as successfully modeled by the Manufacturing Demonstration Facility at Oak Ridge National Laboratory and Oracle's Innovation Lab in Chicago.

The program would be administered by the DOC through the MEP, leveraging its existing relationships with thousands of SMM across the country. By co-locating these facilities within existing manufacturing clusters, the program would also facilitate knowledge sharing and technological diffusion throughout regional innovation ecosystems.

Risks

Implementation challenges could undermine AMEAP's effectiveness. First, equipment procurement at scale requires a) supplier ability to meet the demand, and b) significant upfront

[127] Industry Site Visit, April 3, 2025.

capital that may compete with other priorities. Second, there may be market distortion if government-backed leases create unfair advantages for certain manufacturers, potentially triggering industry pushback or World Trade Organization complaints. Third, successful adoption depends on workforce readiness—employees must be capable of operating advanced systems, which could limit implementation without complementary training investments. Finally, IP concerns could inhibit participation, as companies may hesitate to use shared equipment for proprietary processes without robust data protection protocols.[128]

Supply Chain: Strengthen U.S. Supply Chain Resilience Through Public-Private Partnership and Prioritization

Strategic Rationale

The establishment of robust PPP to procure and manage working stock and stockpiles of materials and components critical to AM represents a vital policy option for bolstering the U.S.'s AM capability. Forming a PPP consortium focused on material procurement, which includes the government, SMM, and large firms executing AM, would increase the purchasing power of all parties, shift some financial risk away from private industry, especially cash-constrained SMM, and support an increased demand signal and access to foreign and constrained markets. This type of partnership would also allow for the establishment of national stockpiles, which would support the stabilization of domestic markets, protect the U.S from global supply shocks, and better align AM capacity with national security needs.

Implementation

Implementation of this policy would require two critical components. The first is prioritization. The materials and components critical to AM cover a wide spectrum, which ranges

[128] Zhang et al., "Digital Twins for Additive Manufacturing," 5.

from raw materials and industrial chemicals to advanced sensors and chips. To avoid diluting effort or overwhelming available financial resources, efforts must be made to identify the most critical materials. This assessment should be based on procurement risk factors such as export restrictions, control of foreign markets by hostile nations, scarcity, and price volatility, as well as impact assessments, which identify the most crucial AM processes and the most critical AM outputs.

Once critical materials and components are identified, the PPP would collate item-specific demand by identifying industry requirements, as well as reasonable quantities to support a national stockpile. The required quantity for a given period could then be procured by the government, maximizing purchasing power and leveraging national-level trade agreements. Industry firms would enter into an agreement to purchase their required quantities of the material from the government at a known price range, based on global market conditions. Excess material could then be sold to firms at a negotiated price or kept as a stockpile. Through iterations of prioritization and procurement, the government could offer decreased prices of procured material as a type of industrial policy to generate AM growth to support a specific industry or geographical area. As with the Strategic Petroleum Reserve, the government could assess markers and domestic usage and sell off material determined to be in excess of stockpile requirements.

Risks

Some risks exist in trying to identify strictly AM material and components. As an industry, AM does not have unique material requirements. Many of the materials critical to AM are critical to multiple industries. At the national level, demand for these items could be pooled across industries to create even greater purchasing power. This would create some challenges with the prioritization process, which would need to be addressed. However, expanding the pool of firms included in the PPP would not only strengthen U.S. AM capacity, but it would also increase the demand for AM implementation, as many of the firms that would be included utilize AM processes to manufacture their products.

The rapid advance of technology also poses a potential risk to this policy. Technological advancements coupled with the government's tendency to be slow in "turning off" policy could lead to the over-procurement and stockpiling of obsolete material. The engagement of industry in the prioritization process would play a critical role in mitigating this risk.

Workforce: Expand E3 immigrant visa opportunities for legal immigrants to work in manufacturing jobs.

Strategic Rationale

The insufficient number of manufacturing job seekers will constrain the U.S.'s ability to reshore industry. Immigration is one policy tool that can assist in closing some of the anticipated job vacancies. During the first Industrial Revolution, expanded labor needs required more people, and first and second-generation immigrants overwhelmingly filled this need.[129] In addition to bolstering workforce numbers, immigrants can be recruited to specific areas, mitigating the challenges posed by the younger, non-migratory generation.

Implementation

Third preference (E3) immigrant visas (IV) are utilized for workers who require two years of study or job training and other unskilled workers requiring less than two years of training. Overall, total visa numbers are capped at 28.6% of the yearly total for all employment-based IV, amounting to approximately 40,000 people annually.[130] The U.S. would need to either expand the

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[129] Charles Hirschman and Elizabeth Mogford, "Immigration and the American Industrial Revolution from 1880 to 1920," *Social Science Research* 38, no. 4 (December 2009): 897–920, https://doi.org/10.1016/j.ssresearch.2009.04.001.

[130] U.S. Department of State. "Employment-Based Immigrant Visas." *Travel.State.Gov*. Accessed May 13, 2025. https://travel.state.gov/content/travel/en/us-visas/immigrate/employment-based-immigrant-visas.html.

overall total of employment-based IVs or increase the percentage of E3 visas relative to the other employment categories to begin closing the number of vacancies within manufacturing positions. To target expanded E3 IV toward advanced manufacturing-specific occupations, Congress could use the Bureau of Labor Statistics Standard Occupational Classification (SOC) system to identify jobs associated with manufacturing careers that would have preference over other occupations. The SOC already has classifications for such positions as Computer Numerical Controlled machine operators, which are heavily used in AM.

Risks

Increasing legal immigration to support manufacturing jobs carries a high risk within the court of public opinion. One of the chief narratives that can take root is the perception that American citizens' career opportunities are being given to non-native citizens. It is possible to blunt the effectiveness of this narrative by emphasizing the precedence for this policy. Immigrants have historically supplemented American labor dating back to the Industrial Revolution in the early 20th century. Another possible talking point is that expanded legal immigration is in response to manufacturing workforce shortfalls in specific areas that cannot be fulfilled by local populations.

Industrial Policy: Renew and expand the Strengthening Community Colleges Training Grants (SCCTG).

Strategic Rationale

There are approximately 1,022 community colleges across the U.S. educating 8.8 million students.[131] Community colleges are the primary post-secondary vehicle for Career Technical

[131] "Community College Facts at a Glance," U.S. Department of Education, accessed May 5, 2025, https://www.ed.gov/higher-education/find-college-or-educational-program/community-college/facts-at-a-glance.

Education (CTE) programs, which prepare students for in-demand occupations.[132] The push toward revitalizing manufacturing careers will require investments to keep CTE programs afloat in local communities. Yet there is a funding disparity between four-year and two-year colleges. Public two-year colleges receive only half the revenue of four-year colleges.[133] Maintaining federal funding streams in addition to local and state resources for community colleges will allow these educational institutions to prepare community members with needed skills for a fraction of the time and cost of a university education.

Implementation

Federal funding, on average, provides an estimated 18% of a community college's revenue.[134] One of the more recent funding programs Congress initiated was the Department of Labor's SCCTG. This $200 million federal grant program provided five rounds of grants aiming to build community colleges' capacity to meet the skill development needs of employers and support students in obtaining good jobs in in-demand industries such as advanced manufacturing.[135] One community college used its SCCTG money to create a system of awarding micro-credentials in specific occupational clusters, allowing participants to gain entry-level jobs quicker.[136] Federal grants will provide community colleges access to funds that will allow them to better serve the manufacturing industry in their local area by initiating workforce training programs that can provide pre-employment skills, reskilling, and upskilling for successful manufacturing careers for a variety of constituencies.

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[132] U.S. Government Accountability Office, *Career and Technical Education: Perspectives on Program Strategies and Challenges*, GAO-22-104544, March 2022, https://www.gao.gov/assets/gao-22-104544.pdf.

[133] "Public Funding of Community Colleges," *Community College Research Center*, accessed May 5, 2025, https://ccrc.tc.columbia.edu/publications/public-funding-community-colleges.html.

[134] "Public Funding of Community Colleges."

[135] "Strengthening Community Colleges Training Grants Program," U.S. Department of Labor, accessed May 5, 2025, https://www.dol.gov/agencies/eta/skills-training-grants/scc.

[136] Matthew Dembicki, "A Glimpse at How SCCT Grants Are Working," Community College Daily, February 6, 2024, https://www.ccdaily.com/2024/02/a-glimpse-at-how-scct-grants-are-working/.

Risks

The primary risk is that the increased funding through grants does little or nothing to channel additional people into manufacturing careers. Some causes of this risk may be other outside factors, such as continued negative perceptions of manufacturing careers, different career options, or other unknown factors. One method for mitigating the risk is to conduct program reviews to ensure that the public money is having its intended effect.

DoD Policy Recommendations

Technology: Leverage existing DoD funds to incentivize the adoption of AM technology within the DIB.

Strategic Rationale

The DoD accounts for about 47% of U.S Government discretionary spending annually, making it the Department with the most opportunity to affect the scale of technology adoption from the federal level. The DoD spent $142 billion on procurement in 2023.[137] The U.S. should use the existing defense budget to target new weapon systems, allowing companies to design for modern manufacturing from the beginning of the product's life, enabling the capture of government incentives to ensure a return on investment to manufacturers who employ new technologies.

Implementation

The DoD should incentivize DIB prime and subcontractors to adopt AM technologies. These incentives could take many forms, including (1) profit incentives for the use of AM technologies, (2) inclusion of AM technology in source selection criteria, (3) use of AM

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[137] *"How Much of the Federal Budget Is Discretionary Spending?"* USAFacts, accessed April 30, 2025, https://usafacts.org/articles/how-much-of-the-federal-budget-is-discretionary-spending/.

[138] International Federation of Robotics, "Global Robot Density in Factories Doubled in Seven Years," *International Federation of Robotics*, accessed April 24, 2025, https://ifr.org/ifr-press-releases/news/global-robot-density-in-factories-doubled-in-seven-years.

technology as a justification for sole source approval, and (4) the inclusion of AM technology in Joint Requirement Oversight Council approved requirements. Defense companies operate on relatively small profit margins compared to other industries. Lockheed Martin, earned 10.9% operating profit in 2023, compared to Apple's 44% profit margin. Limits on defense profitability make sense because the government bears the investment risk in cost-plus contracts, but limits affect a company's investment decisions.[139] Current statutory regulations on profits include incentives for advanced technology.[140] These incentives should be expanded to include incentives for using AM technologies in defense production.

ROBOT RENAISSANCE[ERROR! BOOKMARK NOT DEFINED.]

China is aggressively modernizing its manufacturing sector by using federal subsidies to incorporate robotic technologies. Due to this increased demand, domestic and international robot suppliers have established production plants in China to feed this growth.

The results are impressive. China has a high robot density at 470 robots per 10,000 employees, which ranked third in the world in 2024. More impressively, China only entered the top 10 five years ago and has managed to double its robot density in under four years.

In comparison. The U.S. ranks tenth in the world with 295 per 10,000 employees while France is nineteenth with 186.

Risks

Simply raising profit margins will not provide the incentive necessary to ensure defense companies invest in AM technologies. The Office of the Secretary of Defense (OSD) should prioritize critical investment areas and fund program offices to establish incentives as outlined above to drive technology adoption. OSD must be specific in prioritizing and defining AM

[139] Gregory C. Allen and Doug Berenson, "Why Is the U.S. Defense Industrial Base So Isolated from the U.S. Economy?," *Center for Strategic and International Studies*, August 20, 2024, https://www.csis.org/analysis/why-us-defense-industrial-base-so-isolated-us-economy.
[140] "DFARS 215.404-71-2 Performance Risk."

technologies to ensure these investments are targeted at the most important technologies. Without this definition, the DoD runs the risk of providing increased incentives without achieving the intended return of growing AM technology adoption within the U.S. manufacturing sector.

Supply Chain: Invest in providing Cybersecurity Maturity Model Certification (CMMC) compliant networks to SMM to grow the DoD supply chain.

Strategic Rationale

The consolidation of the DIB in the late 1990s reduced and often eliminated redundancy in DIB supply chains. "Small business participation in defense procurements as prime and subcontractors is vital to the defense mission, competition, and the health of the DIB. Small businesses spur innovation, represent the majority of new entrants into the DIB, and, through their growth, create a pipeline of the next generation of suppliers with diverse capabilities to support the DoD mission."[141] The DoD must continue to remove barriers preventing SMM from participating in defense procurements. In the Vital Signs 2025 survey, 63% of private sector respondents listed "complex and protracted procurement processes" as a pressing factor affecting their ability to work with the DoD. Additionally, 50% listed "burden and risk of compliance with government contracting requirements" as another pressing factor.[142]

Implementation

Manufacturing and Digital Institute, the Manufacturing Institute for Digital Manufacturing and Cybersecurity, identified the need for a "crowd-sourced" cybersecurity solution to help SMM meet DoD's CMMC requirements. MEPs, like the Illinois MEP, try to support companies in

[141] U.S. Department of Defense, *State of Competition within the Defense Industrial Base*, Washington, DC: Department of Defense, February 2022,13, https://media.defense.gov/2022/Feb/15/2002939087/-1/-1/1/state-of-competition-within-the-defense-industrial-base.pdf
[142] Stewart et al., *Vital Signs 2025*, 39.

obtaining CMMC compliance, but they can only provide consulting support; they are unable to help defray the costs beyond limited state grants.[143] The DoD should fund the development of a Controlled Unclassified Information CMMC-compliant network that can be provided for a minimal cost to domestic manufacturers looking to enter the DoD supply chain. Many SMM identified CMMC compliance as a significant barrier to working with the DoD and DIB primes. Not only is CMMC compliance expensive, but it is also manpower intensive and requires unique skillsets that many manufacturing companies do not employ. By building the network and providing it to manufacturers, the DoD ensures the security of its weapon systems, and SMM benefit from the economies of scale of many companies being on the same network.

THE COST OF DOING BUSINESS

SMM looking to work with DIB primes also face the challenge of proving certified cost and accounting data in compliance with government regulations. The Truthful Cost or Pricing Data Act requires compliant financial reporting for all efforts over $2 million. The DoD should also consider developing user-friendly web-based financial software that SMM can use to provide compliant financial data to DIB primes. Mandating DIB primes to accept the government-provided software reporting will take the burden off small companies of tailoring their financial reporting to meet the needs of many customers and instead allow them to focus on manufacturing innovation and growing capacity.

The National Association of Manufacturers estimates the average cost of compliance with federal manufacturing regulations as $29,100 per employee, but it can be as high as $50,100 per employee for companies with less than 50 employees.[144144] With 74% of manufacturing companies employing less than 20 people, reducing the cost burden is crucial to rebuilding the industry.[145145]

[143] Industry Site Visit, April 3, 2025.
[144] National Association of Manufacturers, *The Manufacturing Workforce Crisis: Closing the Skills Gap and Addressing the Talent Shortage*, November 2023, https://nam.org/wp-content/uploads/2023/11/NAM-3731-Crains-Study-R3-V2-FIN.pdf.
[145] National Association of Manufacturers. *Manufacturing in the United States*. Accessed April 24, 2025. https://nam.org/mfgdata/.

Risks

Providing CMMC-compliant networks to SMM will require significant investment from the DoD. Funding this effort will require the DoD to take risk in another mission area. Additionally, the DoD will have to protect SMM IP. However, the risk of not providing a network solution is even greater. By continuing to operate without CMMC-complaint networks, the DoD risks compromising critical new technology. Manufacturing is the top cyber target with most attacks targeted at SMM.[146] In addition to compromising defense technology, these attacks are also costly for SMM, further crippling the U.S.'s limited manufacturing.

Workforce: Revector the mission of the Office of Local Defense Community Cooperation to leverage the 800+ military facilities across the U.S. and align local, state, and federal resources geared toward manufacturing.

Strategic Rationale

One of the chief problems associated with the workforce is bringing resources from educational opportunities, apprenticeships, and actual manufacturing companies to the local workforce pipelines. Some local manufacturers were unaware of federal efforts related to manufacturing.[147] The Office of Local Defense Community Cooperation (OLDCC) would be the logical office to bridge this divide and unite disparate elements. It already has whole-of-government partnerships with the Departments of Labor, Commerce, Transportation, and others. One of the programs under OLDCC's purview is the Defense Manufacturing Community Support Program. This competitive grant program supports long-term community investments that

[146] "Top Cyber Threats in Manufacturing," *Manufacturing x Digital (MxD)*, February 13, 2025, https://www.mxdusa.org/2025/02/13/top-cyber-threats-in-manufacturing/.
[147] Industry Site Visit, April 4, 2025.

strengthen national security innovation and expand the capabilities of the defense manufacturing industrial ecosystem. In FY25, there were zero funded grants for this initiative.[148]

Implementation

The new OLDCC mission would transition it from serving as grant providers to the role of facilitating and implementing expanded outreach efforts related to AM. Suggested efforts include: (1) adding manufacturing education to existing local STEM initiatives to help spread the word about modern manufacturing as a career, (2) implementing a Military to Manufacturing program, like Troops to Teachers, to help move military personnel into post-service manufacturing careers, (3) getting talking points for advanced manufacturing into the hands of Base Commanders for use during community engagement events, and (4) holding AM job fairs across DoD facilities to bring together different federal, state, local entities, manufacturers, local workforce pipelines, and defense industrial base companies.

Risks

Using an existing office substantially lowers the risk of financial resource loss. The major associated risk is the OLDCC's expanded mission could exceed current office manpower support. The pivot away from a grant allocation program may create public concern, but the underutilization of the existing program compared to the community benefits of the proposed approach should mitigate any pushback.

Conclusion

The increasingly competitive international environment is threatening U.S. interests and national security. To counter this threat, the U.S. needs to accelerate the adoption of AM

[148] "Defense Manufacturing Community Support Program | Office of Local Defense Community Cooperation," *Office of Local Defense Community Cooperation*, accessed May 2, 2025, https://oldcc.gov/our-programs/defense-manufacturing-community-support-program.

technologies across both commercial and defense sectors. The adoption of the seven recommended policy options will integrate DoD and whole of government efforts to revitalize the industrial sector and reaffirm the U.S. as a manufacturing power capable of sustained military action anywhere in the world.

Appendix A: Artificial Intelligence

AI Impacts to Manufacturing

AI conceptually is the ability for a computer program to do things that require human intelligence. Per the Congressional Research Office, this generalizes to "learning, problem-solving, and goal achievement under uncertain and varying conditions, often with varying levels of autonomy."[149] These methodologies enable computers to analyze vast datasets, identify complex patterns, make accurate predictions, and optimize processes with minimal human intervention. AI as the most general term can be subdivided into a few major areas, including machine learning (ML), which finds patterns in data; computer vision, which makes sense of the visual world; and natural language processing, which makes sense of the human language.[150] While the AI field has existed since the 1950s and has been actively explored for decades, it has exploded into the global zeitgeist due to advances in ML, specifically one of its subsets, Generative AI (GenAI). GenAI leverages Large Language Models and the concept of Deep Learning to characterize large datasets and generate new insights and meaning. Most of this paper will focus on GenAI, a subset of the overarching concept of Artificial Intelligence. The scope of this paper is limited to AI manufacturing use cases, so there will not be a deep dive into the details of ***how*** AI accomplishes these insights, but we will explore ***what*** the AI needs to accomplish this.

Training AI models requires large volumes of relevant task-specific data along with the necessary governance to keep that data updated and accurate. Firms must first achieve a high degree of digital maturity implementing interoperable and internet-connected platforms to build a digital thread that extends throughout their operations. The closer a manufacturer can get to a "single source of truth", the more advanced the AI possibilities.[151] The tendency to segment data supporting finance, operations, manufacturing, and supply chain management within manufacturing companies is a major hurdle; entrenched, multiple legacy Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) software instances per manufacturer are often tied to decentralized organizational ownership, making holistic data integration a complex and resource-intensive challenge.[152] Granting AI access to more complete, accurate datasets yields substantive improvements in predictive maintenance, adaptive scheduling, quality assurance, and autonomous optimization of manufacturing processes.

In that vein, achieving the promise of Industry 4.0 serves as a necessary precursor to implementing AI in the manufacturing setting. End-to-end digitization of the factory floor with sensors throughout the production process produces a digital thread that serves as the informational foundation for AI to draw meaning and provide insights. When physical tools that manufacture products are interconnect with digital sensors, that data enables feedback loops that can automatically and dynamically change production for optimized output. This same data provides increased insight into the tools and the products they create, enabling predictive

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[149] Laurie A. Harris, *Artificial Intelligence: Overview, Recent Advances, and Considerations for the 118th Congress*. Congressional Research Service, August 4, 2023. https://www.congress.gov/crs-product/R47644.

[150] Matthew Finio and Amanda Downie. "How is AI being used in manufacturing?" *IBM Think*, November 15, 2024. https://www.ibm.com/think/topics/ai-in-manufacturing.

[151] Industry Site Visit, March 13, 2025. This is how Palantir describes the data-centric baseline necessary for organizations to then apply AI to their operations.

[152] Industry Site Visit, April 3, 2025.

maintenance based on performance instead of following unreliable preventative maintenance schedules. Extending that digital thread upstream towards to factory suppliers creates the basis for AI-driven supply chain management that's informed by real-time factory realities. Stretch the tread a farther back to the design phase enables AI to align design performance goals with cost in a closed, accelerated feedback loop, presenting new design opportunities that react to supply chain shocks or manufacturing realities at the factory. Returning to the factory floor, extending that digital thread downstream towards product delivery and front office activities enables AI to dynamically reprioritizing production goals based on strategic requirements. And finally, extending that thread even farther to receiving customers creates the infrastructure necessary to have mine-to-market traceability and audibility.

Creating this digital thread enables AI to optimize and interweave every layer of manufacturing, but it additionally increases the cybersecurity vulnerability of the entire production operation and requires robust protection to prevent IP theft, unplanned downtime, or worse.[153] This risk will be explored in Section 3: AI Risks in Manufacturing

AI and Advanced Manufacturing Technologies

As described by Gartner, a multinational advisory and research firm, the most lucrative and feasible applications for AI in advanced manufacturing technologies generalize to smart operations and logistics, AI-enabled product development, and AI-enhanced automation through robotics (see highlights in Figure 1). Thematically the yellow highlighted areas target routine cognitive functions and enable operations to shift from reactive problem-solving to proactive, predictive strategy implementation. Even the most advanced manufacturers still have information silos at various segments of their operations chain, and these tools exemplify how AI can move manufacturing to the next level.

[153] Cybersecurity and Infrastructure Security Agency and Federal Bureau of Investigation, *Secure by Demand: Priority Considerations for OT Owners and Operators*, January 2025, https://www.cisa.gov/sites/default/files/2025-01/joint-guide-secure-by-demand-priority-considerations-for-ot-owners-and-operators-508c_0.pdf.

GenAI Use-Case Prism for Manufacturing

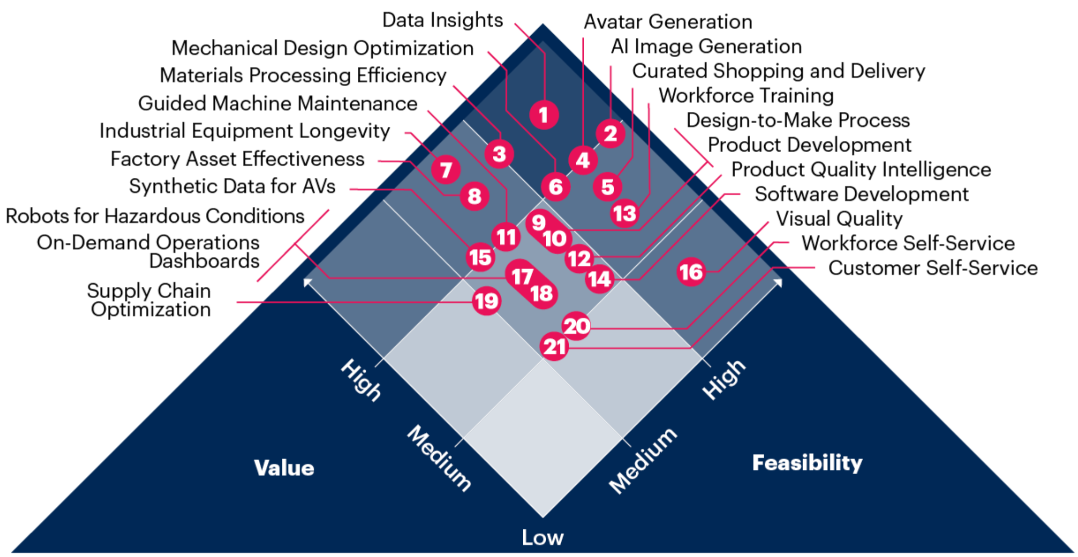

Figure 1- GenAI Use-Case Prism for Manufacturing.
Source: Ellen Eichhorn and Sohard Aggarwal, Use-Case Prism: Generative AI for Manufacturing (Gartner, July 13, 2023), ID G00797407.

Smart Operations and Logistics

This domain focuses on applying AI to optimize the core planning, execution, and maintenance functions within manufacturing operations, often by enhancing existing enterprise systems or introducing new predictive capabilities. The first and most common enabler of manufacturing operations is ERP software. It manages business finances, human resources, inventory, production planning, and supply chain management. Frequently companies have multiple ERPs that are customized for specific needs within those segments, and each is functionally a data silo with only limited connectivity between them. AI is already making ERPs more functional by increasing data quality; financial data historically kept on customized spreadsheets are being ported into the databases of larger system of record by helping employees generate implementation code and customization without the need for external consultants. SMM are particularly helped because AI can bridge the skill gap found at smaller businesses that can't afford dedicated information technology (IT) development staff. [154]

MES connect real-time factory floor management with requirements from an ERP. They enable order flow prioritization, job order taskings by shift and by machine, and ultimately synchronize employees, tools, materials, and machine programming.[155] MES software empowered with AI can oversee an entire production process end-to-end tirelessly, and when trained properly, dynamically catch defects in real time and even update the production process within prescribed boundaries to meet production performance specifications. For example, in the

[154] Tony Bradley, "Disrupting the ERP Market with AI," Forbes, March 27, 2024, https://www.forbes.com/sites/tonybradley/2024/03/27/disrupting-the-erp-market-with-ai/.
[155] Adrian Stelmach, "AI Meets Manufacturing: The Smart Evolution of MES," Forbes, March 13, 2025, https://www.forbes.com/councils/forbesbusinesscouncil/2025/03/13/ai-meets-manufacturing-the-smart-evolution-of-mes/.

automotive and steel sector, AI applied in a MES can inspect the paint job for every produced car, find microbubbles humans would only find in quality assurance/quality control for some sub percentage of frames, and verify the torque on every single screw. If empowered, AI can direct remediation of any shortfalls or team with a human to make the most appropriate decision. When armed with the right sensors, MES and AI are also the means to conducting predictive maintenance on expensive tools based on performance instead of just waiting for a time- or use-based automatic preventative maintenance service schedule. Servicing machines prior to failure limits downtime and minimizes overall repair costs.[156]

Zeroing in on the supply chain management aspect of ERPs, AI is enabling manufacturers to move from responding to delays and disruptions towards anticipating and preparing for them using tools like Oracle NetSuite.[157] With the right software, they are able to continuously analyze supplier performance and availability, geopolitical realities (e.g. tariffs), delivery timeline requirements, transportation costs, existing orders, and more to find disruptions and bottlenecks through the power of predictive planning. Xometry, an additive manufacturer that specializes in low-volume, high-mix production, has effectively created a virtual high-volume, high-mix capacity and supply chain; by merging their order flow with downstream original equipment manufacturer partners, they are able to reliably fulfill much larger orders at faster speeds and leverage thousands of vetted SMM.[158] AI enables them to leverage their order stream to effectively unify SMM manufacturers behind one banner and disrupt their market segment.

To bridge the gap between ERP and MES software solutions and apply AI principles, Palantir has partnered with L3 Harris, ShieldAI, Andural, Saronic, and more to pilot their new manufacturing operating system, “Warp Speed”, a new and unique offering in the manufacturing industry. As Palantir likes to say, the tool “reimagines how to bend atoms better with bits”.[159] A new custom solution that consolidates all ERP and MES functions for any one of these manufacturers might take years to develop and deploy, and once deployed, it might not even be the right solution due to changes in technology or process since the requirement was developed. Palantir uses Warp Speed to, in a matter of days to weeks, quickly connect all of a company’s backend databases, recontextualize that data for easy comparison, and ultimately create a single source of truth for the organization to then overlay Warp Speed’s AI options. This is done fast, but it also removes the need for customization of any of those manufacturing systems that are highly specialized and capable for their tasks, saving in some cases hundreds of millions in consulting fees and potentially 18+ months of time that can instead be used to iterate on requirements.[160] AI can then take this information to connect a digital thread from mine to finished product to customer, allowing for seamless optimization of designing, planning, production, supply chain management, and logistics activities.

Product Development

AI is fundamentally reshaping the product development lifecycle by enabling

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[156] Stelmach, "AI Meets Manufacturing.”

[157] Kathleen Walch, "How AI Is Reshaping the Entire Supply Chain," Forbes, February 18, 2025, https://www.forbes.com/sites/kathleenwalch/2025/02/18/how-ai-is-reshaping-the-entire-supply-chain/.

[158] Industry Site Visit, January 16, 2025.

[159] Industry Site Visit, March 13, 2025.

[160] Palantir Technologies, "Palantir Warp Speed Accelerates, Announces Six New Customers That Are Re-Industrializing American Manufacturing," Palantir Investor Relations, March 13, 2025, https://investors.palantir.com/news-details/2025/Palantir-Warp-Speed-Accelerates-Announces-Six-New-Customers-That-Are-Re-Industrializing-American-Manufacturing/.

manufacturers to predict performance, optimize designs, and accelerate innovation. One major area is through the building and usage of Digital Twins. These real-time, virtual replicas of a physical product, process, or system can simulate various operational conditions, predict failures, and identify design flaws before physical prototypes are built, drastically reducing time-to-market and costs. For example, the MXD (Manufacturing x Digital) institute from the National Institute of Standards and Technology's (NIST) Manufacturing USA effort demonstrated AI-enhanced blast furnace simulations that improved steel production efficiency by enabling predictive control strategies previously unavailable through traditional methods.[161]

Another product development area impacted by AI is in design, where generative design tools augment human creativity. By feeding parameters like material strength, weight limits, and manufacturing constraints into AI systems, engineers can explore hundreds or thousands of optimized design alternatives rapidly. In fields like materials science and composites development, AI is helping discover new material formulations faster than traditional experimental methods would allow, providing a competitive advantage in aerospace, automotive, and defense manufacturing sectors.[162]

Robotics

According to NIST, the performance expectations surrounding AI and machine learning in physical manufacturing environments are often unrealistically high.[163] Embodied systems must contend with variability in material conditions, lighting, human interaction unpredictability, and the difficulty of scaling AI beyond narrowly trained tasks. While AI-enabled generalized robotics show extraordinary promise, full-scale deployment across the manufacturing ecosystem requires core AI development in Computer Vision, Natural Language Processing, and substantial investments in sensor fidelity, edge computing, and AI safety protocols before they can be expected to be seen at scale in manufacturing settings.

While one robot to accomplish many tasks is still not expected until the 2030s, single function robotics powered by AI continue to see incremental advancements. According to the New York Times, China is positioned robotics and AI integration as the next critical technology to enable their advanced manufacturing.[164] For example, their *Made in China 2025* effort has produced a domestically manufactured, affordable, AI-enabled robotic welding arm that can replicate human actions with minimal training. In only four years, China has managed to drive this tool cost down to $40k instead of the $140k foreign-made equivalent.[165] At this price point, even SMM in China's Guangzhou district have started adoption at scale. This systemic shift not only mitigates the challenges posed by China's impending demographic decline, but also enhances their ability to maintain global competitiveness in mass production.

U.S. firms are pursuing higher-performance innovations at the intersection of AI and advanced robotics. On the embodied AI front, companies like Boston Dynamics are pioneering

[161] MxD, "How Digital Twin Technology-and a Virtual Blast Furnace-Are Helping to Bridge the Manufacturing Skills Gap," *MxD*, January 14, 2025, https://www.mxdusa.org/2025/01/14/how-digital-twin-technology-and-a-virtual-blast-furnace-are-helping-to-bridge-the-manufacturing-skills-gap/.

[162] Industry Site Visit, February 6, 2025.

[163] Elena R. Messina, *Research Opportunities for Advancing Measurement Science for Manufacturing Robotics* (Gaithersburg, MD: National Institute of Standards and Technology, 2024), https://doi.org/10.6028/NIST.GCR.24-054

[164] Keith Bradsher, "China's Secret Weapon in the Trade War: Factory Robots," *New York Times*, April 23, 2025, https://www.nytimes.com/2025/04/23/business/china-tariffs-robots-automation.html.

[165] Bradsher, "China's Secret Weapon in the Trade War: Factory Robots."

warehouse automation with robots capable of adapting dynamically to changing inventories and facility layouts.[166] Manufacturers like FANUC America are embedding AI into robotic arms to enable real-time error correction, predictive maintenance, and adaptive task learning without constant reprogramming.[167] Furthermore, AI is making automation more accessible because programming robots now can be accomplished with generative AI front ends that translate requirements into machine code without the operator having to learn the details.[168]

Comparative Assessments of China and the United States

As assessed by Stanford University, the U.S. still leads in producing top GenAI models, but China is closing the performance gap**.** Throughout 2024, U.S.-based institutions produced the best leading-edge models and associated datacenter infrastructure to power them, out producing China 40 to 15.[169] Chinese models have rapidly closed the quality gap China but export controls limiting China's access to leading edge compute technology from Nvidia has set the stage for them to become self-sufficient.[170] China's emphasis on developing domestic, low-cost, AI-enabled manufacturing technologies has begun to bear fruit, but their comparative advantages in labor costs has focused their investment in high volume, low mix environments with high capex requirements.

AI Risks in Manufacturing

The inherent opacity of trained AI models introduces significant risks in manufacturing environments, especially concerning their lack of interpretability and auditability. They derive their decision-making capabilities from extensive training datasets that combine to produce a "black box" final product (i.e. the user of the model knows what goes in and what comes out but does not understand the inner workings). The trained model produces answers with high accuracy, but humans are often unable to fully discern or understand how these models arrive there. This makes it challenging or even impossible to identify potential vulnerabilities, adversarial backdoors, biases, or otherwise.[171]

In manufacturing contexts with AI-driven physical machinery or critical quality assurance systems, this black box quality is a serious risk factor. Current capabilities cannot reliably or comprehensively audit complex neural models for hidden backdoors or aberrant behaviors, and companies could unknowingly be exposed to vulnerabilities. These backdoors could be embedded intentionally through data poisoning or inadvertently through biased or corrupted training datasets. Without thorough auditing capabilities, manufacturers face uncertainty regarding AI reliability, safety compliance, and cybersecurity risks, potentially compromising operational integrity, product safety, and business continuity.

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[166] Boston Dynamics, "Atlas Goes Hands On," *Boston Dynamics*, 2024, https://bostondynamics.com/video/atlas-goes-hands-on/.

[167] Breana Noble, "Artificial Intelligence Helps Robot Supplier Fanuc Expand in Oakland County," *The Detroit News*, July 10, 2024, https://www.detroitnews.com/story/business/autos/2024/07/10/artificial-intelligence-robots-fanuc-expand-auburn-hills-michigan/74285514007/.

[168] Noble, "Artificial Intelligence Helps Robot Supplier Fanuc."

[169] Stanford University, *Artificial Intelligence Index Report 2025* (Stanford, CA: Stanford University, 2025), 3.

[170] Stanford University, *Artificial Intelligence Index Report 2025* (Stanford, CA: Stanford University, 2025), 4.

[171] Samuel Hammond, "Testimony before the U.S. House Committee on Science, Space, and Technology: The State of U.S. Science and Technology: Ensuring U.S. Global Leadership," February 5, 2025, Foundation for American Innovation.

This black box quality creates two risk factors to AI-driven manufacturing. First, Daniel Carpenter of Harvard argues that this is not just a technology problem; there is no governance structure that could even begin to audit AI as it is adopted across manufacturing industries.[172] While there may be a reason to try to slow the development of AI in the name of safety, the main step that manufactures should follow is to ensure they have sufficient, layered risk controls in place to protect their interests.

Second, robotics and tools tied to AI rely upon sensors and frequently reside on a local area network that can potentially be attacked by malicious actors. Deloitte and the manufacturing industry refer to this network segment as the Operational Technology (OT) network, which contrasts with the IT network where all normal business computer, printers and regular internet browsing occurs.[173] If the underlying network is not secure, then any AI that relies upon data from the OT segment can be put at risk. As Deloitte outlines, surveys show that many manufacturers try to create security by segmenting that network, but this creates a new problem; if the machines and sensors in a Smart Factory cannot be secured and connected to an AI for improved performance, then what use is AI? Also, while large manufacturers have the money and scale to justify dedicated staff focusing on security, how are SMM manufacturers supposed to protect against this kind of issue?

The US Government has attempted to shore up this shortfall at least within the Department of Defense industrial base through the establishment of the CMMC 2.0 process, recently put into force December of 2024.[174] The process is arduous and time consuming, primarily applies only to the prime contractor, but it is a beach head of security that can help to test bed new security innovations going into the future. The Department of Homeland Security's Critical Infrastructure Security Agency publishes "cross-sector cybersecurity goals" to aid small- and medium-sized businesses in implementing NIST's Cybersecurity Framework, but these all require dedicated manpower to implement – a luxury most SMM manufactures cannot afford.[175]

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172 Daniel Carpenter and Carson Ezell, "An FDA for AI? Pitfalls and Plausibility of Approval Regulation for Frontier Artificial Intelligence," *paper presented at the AAAI/ACM Conference on AI, Ethics, and Society*, San Jose, CA, 2024.

173 Deloitte, "Cybersecurity for Smart Factories in the Manufacturing Industry," *Deloitte Insights*, https://www2.deloitte.com/us/en/pages/energy-and-resources/articles/smart-factory-cybersecurity-manufacturing-industry.html.

174 Small Business Administration, Office of Advocacy, "DOD Issues Final CMMC Rule," *Office of Advocacy*, October 24, 2024, https://advocacy.sba.gov/2024/10/24/dod-final-cmmc-rule/.

175 Cybersecurity and Infrastructure Security Agency (CISA), *Cross-Sector Cybersecurity Performance Goals*, March 2023, https://www.cisa.gov/cross-sector-cybersecurity-performance-goals.

Appendix B: Wargaming

Recent global conflicts and supply chain crises have underscored that the U.S.'s ability to "fight tonight" rests not only on current military capabilities but also on the strength and responsiveness of its DIB. AM technologies provide cutting-edge capabilities for the U.S. military and its allied and partner nations. However, these same technologies often rely on complex global supply chains and scarce materials. This raises a sobering question for strategists: What happens if we cannot get our stuff? To answer this, defense planners increasingly use wargaming to simulate severe supply chain disruptions and contested logistics environments. By modeling scenarios in which critical materials, components, or systems become inaccessible, wargames can reveal vulnerabilities and test potential solutions, such as domestic surge production, allied collaboration, or pre-positioning of stockpiles. This annex analyzes the role of wargaming in evaluating and enhancing surge capacity and resilience in advanced manufacturing for the U.S. and allied partners' innovation and DIBs. It examines how wargames simulate supply chain shocks and contested logistics, discusses insights from recent exercises, and explores the strategic role of AM in military operations.

Wargaming Industrial Base Resilience and Surge Capacity

Wargames have long been used by the DoD and its think tanks to anticipate battlefield dynamics. Today, they are applied to the often-overlooked battles behind the lines, those of production and supply. Surge capacity refers to the ability of the industrial base to rapidly scale up production of defense materials, such as weapons, equipment, and spare parts, in response to a crisis or conflict. Resilience denotes the robustness of supply chains to withstand shocks and adapt to stress. Traditional acquisition processes and lean manufacturing practices have optimized efficiency in peacetime, but they have also squeezed out excess capacity, creating vulnerable supply chains that struggle to respond to sudden demand spikes.[176] The COVID-19 pandemic and Russia’s invasion of Ukraine exposed these issues, from microchip shortages to dwindling stockpiles of munitions.[177] In Ukraine's case, Western arsenals found that replacing 155mm artillery shells or Stinger missiles was neither quick nor easy; production lines lay unproductive or at minimal output, and ramping them up proved to be an 18-month endeavor in some cases.[178] Such lessons have spurred U.S. defense officials and analysts to call for greater focus on industrial base war preparedness. As one commentary noted, it is imperative to treat the industrial base as a foundational element of warfighting and even to require formal Title 10 wargames centered on the industrial base and supply chains so that senior military leaders, who often have operational

[176] Cynthia R. Cook, “Reviving the Arsenal of Democracy: Steps for Surging Defense Industrial Capacity,” *Center for Strategic & International Studies (CSIS)*, March 14, 2023, https://www.csis.org/analysis/reviving-arsenal-democracy-steps-surging-defense-industrial-capacity; Christopher Hernandez-Roy, Henry Ziemer, and Alejandra Toro, “Mining for Defense: Unlocking the Potential for U.S.-Canada Collaboration on Critical Minerals,” *Center for Strategic & International Studies (CSIS*, February 18, 2025, https://www.csis.org/analysis/mining-defense.

[177] Sandra R. Thomas, “Defense Industrial Base Sector Won’t Surge Without Policy Changes,” National Defense Magazine, April 7, 2025, https://www.nationaldefensemagazine.org/articles/2025/4/7/defense-industrial-base-sector-wont-surge-without-policy-changes. ; Cynthia R. Cook and Christine Michienzi, “How to Ensure the Defense-Industrial Base and Supply Chain Resiliency,” Defense News, September 19, 2023, https://www.defensenews.com/opinion/2023/09/19/how-to-ensure-the-defense-industrial-base-and-supply-chain-resiliency/.

[178] Thomas, “Defense Industrial Base Sector Won’t Surge Without Policy Changes.”

backgrounds rather than acquisition experience, internalize how deeply "the ability to fight wars depends on a strong industrial base."[179]

Within the DoD, offices are now wargaming scenarios of national mobilization and supply chain disruption to drive home these points and inform policy. In response to a congressional mandate, the OSD and the services have started conducting tabletop exercises (TTX) examining large-scale mobilization and how to rapidly expand the armed forces and industry in a wartime emergency.[180] These games force participants to grapple with questions like: Where would the skilled labor and manufacturing equipment come from to surge the production of missiles or satellites? What if key suppliers in Asia are cut off? Who has the authority to direct civilian industries to prioritize defense needs? By simulating crisis conditions, wargames can reveal gaps in current plans. For example, initial rounds of these mobilization games have highlighted the lack of an updated national mobilization framework, unlike WWII, when agencies had clear assignments for wartime economic management, today, there is no such book of defined responsibilities requiring policy improvisation in a crisis.[181] Wargaming these issues is prompting discussions in the Pentagon about new policies for industrial readiness and surge support. As one defense official put it, the outcomes of such games" should enforce new policy" by identifying who must do what in an emergency and what authorities or resources are missing.[182] In short, wargaming is being recognized as a critical analytic tool to stress-test the defense industrial base, much as warfighters use exercises to stress-test combat doctrines.

Simulating Supply Chain Disruptions and Contested Logistics

A core focus of these industrial base wargames is simulating supply chain disruptions under realistic warfighting conditions. This often means modeling a "contested logistics" environment, in which an adversary actively interferes with the flow of supplies and the DIB. In a high-end conflict against a peer competitor, the U.S. and allied partners may face attacks on supply lines, blockades, cyber disruptions to logistics networks, or even losing access to foreign materials and manufacturing. Wargames allow planners to ask, "What if our normal supply routes and vendors fail?" One notable series is the U.S. Navy's Naval Contested Logistics Wargame, run by the Naval War College. In its 2022 iteration, over 200 participants from across the Navy, Joint Staff, Defense Logistics Agency (DLA), and Allied Partner militaries, such as Australia and Japan, examined how to sustain distributed naval forces in a notional Pacific war scenario.[183] The simulation presented a Pacific Theater where U.S. bases were under missile threat, and traditional seaborne resupply was at risk.[184] The Navy identified from the findings that certain relatively "low-cost investments," in both new concepts of operation and specific capabilities, yielded outsized improvements in keeping forces supplied under attack.[185] In particular, the wargame showed that investments giving commanders greater flexibility, for example, for diversified fuel distribution methods, mobile logistics, or improved interoperability with allied logistics, can significantly

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[179] Cook and Michienzi, "How to Ensure the Defense-Industrial Base and Supply Chain Resiliency."
[180] Thomas, "Defense Industrial Base Sector Won't Surge Without Policy Changes."
[181] Thomas, "Defense Industrial Base Sector Won't Surge Without Policy Changes."
[182] Thomas, "Defense Industrial Base Sector Won't Surge Without Policy Changes."
[183] U.S. Government Accountability Office (GAO), *Defense Analysis: Additional Actions Could Enhance DOD's Wargaming Efforts*, GAO-23-105351 (Washington, DC: GAO, April 2023), 11, https://www.gao.gov/products/gao-23-105351.
[184] GAO, DoD Wargaming Efforts, 11-12.
[185] GAO, DoD Wargaming Efforts, 12.

increase the resilience of the overall system.[186] The game also exposed "significant challenges and opportunities" in delivering sustainment when the enemy might contest every convoy or supply run.[187] These insights have since been fed into real-world planning; Navy officials used the results to shape new logistics concepts and inform decisions about organizing and resourcing distributed support forces.[188] The wargame served as a laboratory to explore how the Navy could adapt its logistics in a future Indo-Pacific conflict, where geographic distance and enemy capabilities create unprecedented strain on supply chains.

Allied defense organizations have run similar exercises to address contested logistics. North Atlantic Trade Organization (NATO), for instance, incorporated a logistics wargame in its recent "STEADFAST" series of exercises, compelling member nations to consider how they would sustain high-intensity operations in Europe if traditional transportation infrastructure were disrupted.[189] At U.S. European Command, American and NATO logisticians conducted a November 2022 wargame to rehearse large-scale reinforcement and sustainment under threat, essential stress-testing the alliance's supply network against potential Russian interference.[190] These scenarios force hard trade-offs; if fuel pipelines or rail lines are severed, how do you prioritize what limited supplies get through? If a supplier of critical components or materials in one country is offline, can another ally's industry pick up the slack? Wargames highlight the value of allied collaboration and interoperability by simulating such contingencies. For example, a NATO logistics exercise in 2023 "emphasized the national responsibility of logistics" while illuminating the need for a collective approach, aligning authorities and stockpiles among allies so that another's surplus might mitigate one nation's shortfall.[191] This merges with a broader lesson: no single country can go it alone logistically in a contested environment. The U.S. and its allies must pre-plan cooperative mechanisms for sharing resources, pooling critical supplies, and using each other's industrial capabilities when under duress.

Wargame scenarios that examine critical supply denial, such as situations where a vital material or component is suddenly inaccessible, are crucial. For example, the U.S. defense enterprise is heavily reliant on certain critical minerals, like rare earth elements, such as samarium, gadolinium, terbium, dysprosium, lutetium, scandium, and yttrium, and high-tech components, such as semiconductors, lasers, and specialty photonics chips, that are significantly sourced from abroad. Analysts and others are running TTX and wargames asking, "What if China were to embargo exports of rare earths during a crisis?" Given that China controls an estimated 70% of global rare earth mining and an even greater share of processing, the results are alarming.[192] The

[186] GAO, DoD Wargaming Efforts, 12.
[187] GAO, DoD Wargaming Efforts, 12.
[188] GAO, DoD Wargaming Efforts, 12.
[189] Paolo Giordano, "NATO Exercise STEADFAST FOXTROT 2023 Concludes," *NATO's Joint Warfare Centre (JWC)*, November 17, 2023, https://www.jwc.nato.int/article/nato-exercise-steadfast-foxtrot-2023-concludes/.
[190] U.S. European Command, "USEUCOM Logisticians Wargame Force Movements, Sustainment with NATO Counterparts," accessed April 30, 2025, https://www.eucom.mil/pressrelease/42235/useucom-logisticians-wargame-force-movements-sustainment-with-nato-counterparts.
[191] Giordano, "NATO Exercise STEADFAST FOXTROT 2023 Concludes."; Jeffrey Appleget, Robert Burks, and Frederick Cameron. *The Craft of Wargaming : A Detailed Planning Guide for Defense Planners and Analysts*. Annapolis, MD: Naval Institute Press, 2020.
[192] U.S. Government Accountability Office (GAO), "Critical Materials Are In High Demand. What Is DOD Doing to Secure the Supply Chain and Stockpile These Resources?," *GAO WatchBlog*, March 20, 2025, https://www.gao.gov/blog/critical-materials-are-high-demand.-what-dod-doing-secure-supply-chain-and-stockpile-these-resources; U.S. GAO, *Defense Analysis: Additional Actions Could Enhance DOD's Wargaming Efforts*.

U.S. currently imports over 95% of the rare earths it consumes, with few immediate substitutes or domestic stockpiles.[193] A wargame built around this scenario might start on "D-Day" of a conflict with an announcement that rare earth shipments have stopped, and within months, production of precision-guided munitions, jet engine alloys, and other high-tech military hardware grind to a halt unless alternative sources are found. We are experiencing the similarity of this scenario now, despite peacetime. Center for Strategic and International Studies (CSIS) recently shared, "On April 4, China's Ministry of Commerce imposed export restrictions on seven rare earth elements and magnets used in the defense, energy, and automotive sectors in response to U.S. President Donald Trump's tariff increases on Chinese products. The new restrictions apply to 7 of 17 rare earth elements—samarium, gadolinium, terbium, dysprosium, lutetium, scandium, and yttrium—and require companies to secure special export licenses to export the minerals and magnets."[194] The Government Accountability Office's (GAO) recent analysis warned that the U.S. currently "doesn't have equivalent substitutes…that perform at the same level.[195] This is a classic example of "what happens if we can't get our stuff?" and only by running the scenarios can strategists identify stop-gap solutions. These strategies might include emergency stockpiling of raw materials, cannibalizing civilian products for parts, tapping allied sources, or activating emergency mines—if they exist within the U.S. or an allied country. Allies can play a huge role. For example, a recent CSIS study highlighted that Canada, with some mineral resources and an existing role in the U.S. defense industrial base, could be a key alternative source for many minerals now dominated by China.[196] A wargame scenario where U.S. allies and partners coordinate to fill the gaps can show considerably better outcomes than a unilateral U.S.-only response.

AM: Strategic Technologies in Play

AM is an area of technology that features prominently in both the vulnerabilities and potential solutions identified by defense wargaming. AM encompasses new production techniques such as ADMAN (3D printing), advanced robotics, and digital design, which can revolutionize how and where things are made. These technologies are double-edged swords in a strategic sense; they offer powerful new military capabilities, but they also often depend on specialized supply chains and know-how that may be concentrated in only a few countries.

Wargames and analyses have started to incorporate AM as a way to bolster surge capacity. One concept is the idea of distributed manufacturing, using 3D printers and modular micro-factories to produce critical parts at the point of need, such as on a forward-deployed naval ship or an airbase, rather than relying entirely on shipments from the homeland. The DoD has recognized the promise of this approach; in 2023, the DLA set up an ADMAN program integration team to explore integrating 3D printing into logistics.[197] Part of this effort included supporting an OSD-led "ADMAN Crisis Action Response" wargame to simulate how on-demand printing could help during a supply chain emergency.[198] Although details of that game remain limited, the mere

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[193] GAO, "Critical Materials Are In High Demand."; GAO, "DoD Wargaming Efforts."
[194] Gracelin Baskaran and Meredith Schwartz, "The Consequences of China's New Rare Earths Export Restrictions," *Center for Strategic & International Studies (CSIS)*, April 14, 2025, https://www.csis.org/analysis/consequences-chinas-new-rare-earths-export-restrictions.
[195] GAO, "Critical Materials Are In High Demand."; GAO, "DoD Wargaming Efforts."
[196] Hernandez-Roy, Ziemer, and Toro, "Mining for Defense."
[197] Defense Logistics Agency, *Fiscal Year 2023 Historical Report*, directed by Vice Admiral Michelle C. Skubic, 2023, https://www.dla.mil/Portals/104/Documents/Headquarters/History/2023AnnualHistory.pdf.
[198] Defense Logistics Agency, *Fiscal Year 2023 Historical Report*.

existence of such an exercise indicates that planners are evaluating scenarios like: should a critical component for fighter jets no longer be sourced from overseas, could deployed forces download a design file and print the part locally to keep jets flying? On the positive side, wargames suggest that having deployable printers for things like drone spare parts or medical supplies could dramatically shorten resupply times and reduce dependence on vulnerable convoys. For instance, the Marine Corps has tested printing drones and equipment in the field as part of its Expeditionary Advanced Base Operations concept.[199] However, challenges include ensuring quality control of printed parts, securing the raw feedstocks, like powders and polymers for printers, and cyber-securing the digital blueprints. Wargamers must consider that an adversary would attempt to corrupt 3D print files or block/corrupt the materials needed for printers. This highlights that advanced manufacturing is not a solution for everything, but one more tool for resilience when used smartly.

If war games set 10-15 years in the future feature these technologies, a key consideration is whether the U.S. and its allies can control the supply and production of the necessary components. An allied advantage could quickly evaporate if an adversary sabotages the supply chain or export controls prevent access to the latest technology. Thus, a consistent theme in wargaming advanced tech is the need for technology sharing among allies and joint development of manufacturing capacity. For instance, the AUKUS partnership (Australia-UK-U.S.) inroads in quantum technology can be seen as preemptively creating a resilient network so that if one nation is cut off, the others can compensate.[200] In summary, AM must be factored into defense wargames. They are critical enablers that must be safeguarded and explored as innovative means to support supply chain challenges.

In conclusion, wargaming has proven to be a valuable methodology for stress-testing the surge capacity and resilience of the U.S. and allied DIB. However, AM must be factored into defense wargames. By simulating "what if" scenarios, from Pacific supply chains under fire to rare minerals being cut off to sudden spikes in demand for high-tech weapons, these exercises transform abstract worries into concrete outcomes that inform strategists, planners, and policymakers. The overarching lesson is that industrial resilience can be as much of a deterrent as military readiness. No adversary will lightly enter a conflict if they know the U.S. and its partners can rapidly overcome disruptions and keep their forces equipped to fight. Achieving that level of resilience will require foresight and investment, precisely the outcomes that insightful wargaming is meant to drive. As the defense community digests these wargame lessons, the hope is that they inform tangible steps to fortify the innovation and industrial bases that underwrite national security. In a future crisis, when the question "Can we get our stuff?" arises, robust preparation should ensure the answer is a confident "yes."

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[199] Johannes Schmidt, Paul Gillikin, and Matt Pine, "How Marines Are 3D Printing Lethality Behind Enemy Lines," *Seapower*, April 11, 2025, https://seapowermagazine.org/how-marines-are-3d-printing-lethality-behind-enemy-lines/.

[200] Josh Luckenbaugh, "AUKUS Nations Making Inroads on Quantum Tech, But Barriers Remain," *National Defense Magazine*, February 21, 2025, https://www.nationaldefensemagazine.org/articles/2025/2/21/aukus-nations-making-inroads-on-quantum-tech-but-barriers-remain.

Appendix C: Stakeholders

AM has a wide range of stakeholders, each with unique and sometimes conflicting interests. The primary stakeholders are manufacturers, workers and labor unions, governments and policy makers, technology providers and innovators, academic and research institutions, and consumers. Manufacturers include companies and enterprises working in manufacturing. These entities are interested in increased productivity and efficiency, high quality, cost reductions, and workforce safety, all resulting in a competitive advantage over their competitors. Workers and labor unions are interested in job security, job safety including repetitive and ergonomically challenging tasks, workplace environment, and upskilling and retraining opportunities. Governments and policymakers are interested in economic growth, national security, job creation, and social stability. The interests of other governments, allies, and adversaries often influence government and policymakers. Sometimes these stakeholders work together to support each other's actions, other times, they intentionally try to compromise the interests of others. Technology providers and innovators are interested in expanding markets for new technologies, collaborations with manufacturers, and IP rights. Technology providers are often unconcerned with the interests of governments and look to expand to reach as many consumers as possible, despite national security concerns. Academic and research institutions are interested in the availability of research funding, building partnerships with industry, and developing the next-generation workforce. Consumers are interested in having access to high-quality, affordable products. Some consumers are also interested in sustainable and ethical production practices.

Business-Government Relations

The U.S. government is closely integrated with the manufacturing industry through the NIST Manufacturing USA initiative. The Manufacturing USA program is a 10-year-old national initiative launched by the U.S. federal government to promote innovation, technology transition, and workforce development in advanced manufacturing. NIST coordinates the program through a network of public-private manufacturing innovation institutes.[201] Each institute focuses on specific technology domains and they are complemented by the MEP program, a parallel nationwide program that provides direct support to SMM.[202] In short, the institutes focus on innovation, and MEP centers focus on extending application of those innovations to our SMM that do not have the staff or capital to afford dedicated innovation efforts. There are currently 17 innovation institutes, all sponsored by either the DoD, DOE, or NIST. They operate as consortia partnered with large manufacturers, universities, startups, and state governments.[203] Each institute focuses on a particular domain such as composites, additive manufacturing, robotics, or photonics, and conducts collaborative research to scale up lab innovations into production-ready technologies.[204] They serve as an anchor for a related industrial cluster and have direct relationships with partners across the country.

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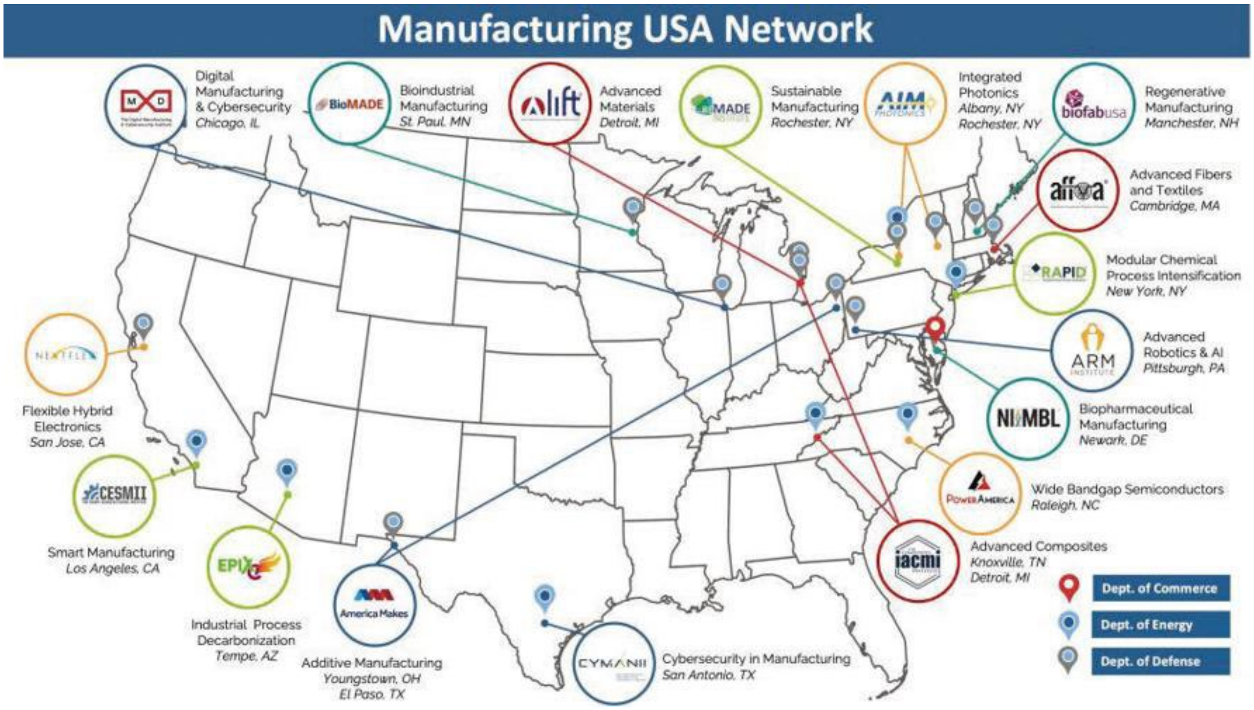
[201] National Institute of Standards and Technology (NIST), *Manufacturing USA: A Third-Party Evaluation of Program Design and Progress* (Washington, DC: NIST, 2021), 4–7.

[202] NIST, Manufacturing USA, 10–12.

[203] Advanced Manufacturing National Program Office (AMNPO), *2022 Manufacturing USA Annual Report* (Gaithersburg, MD: NIST, 2022), 8–9.

[204] AMNPO, 2022 Annual Report, 12-14.



The MEP National Network complements the high-tech focus of the institutes by helping smaller manufacturers improve their operations, adopt existing technologies, and address challenges in areas such as quality control, supply chain resilience, and workforce training.[205] Each state and Puerto Rico has a MEP center, and it works with local businesses to implement solutions tailored to their needs.[206] The MEP's field-based model ensures that small firms without in-house R&D can still access best practices and innovations developed within the Manufacturing USA network.

Institutes and MEP centers work together to form a coordinated pipeline. Institutes develop next-generation technologies and training content, and then MEPs help companies adopt those tools and build the capabilities to use them effectively. NIST has explicitly recognized this complementary relationship, describing how institutes address future capabilities and MEP centers assist with the deployment of existing ones.[207]

Mobilization

The DoD and the DIB are inadequately prepared to mobilize for a large-scale conflict. The DIB is scaled to build at a steady state peacetime pace and does not have excess capacity to enable immediate increases in production quantities. The War in Ukraine presented the U.S. a unique opportunity to increase production rates prior to U.S. engagement in a conflict. The U.S. Congress

[205] NIST, *MEP National Network Annual Report 2022* (Gaithersburg, MD: NIST, 2023), 15–17.
[206] NIST, *MEP National Network Annual Report 2022*, 5.
[207] AMNPO, 2022 Annual Report, 10.

over $174.2 billion in emergency supplemental spending to support Ukraine.[208] The U.S. has used two main mechanisms to provide military support to Ukraine. Presidential Drawdown Authority allows the U.S. President to transfer existing war materials to a country in need. Those war materials are then backfilled, through Congressional appropriations and U.S. DIB contracts, with newer technologies. The Ukraine Security Assistance Initiative enables the Ukrainian government to contract directly with the U.S. DIB for weapons procurement. Both of these programs have provided an influx of funding to the U.S. DIB, demanding increased capacity and testing the ability of the DIB to scale quickly.[209] The weapons being procured for Ukraine would not necessarily be the same weapons required in a conflict in the Indo-Pacific, but this effort did exercise the ability of the DoD and DIB to quick react and mobilize.

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[208] Congressional Research Service, *Defense Production for Ukraine: Background and Issues for Congress*, R48182, March 15, 2024, https://www.congress.gov/crs-product/R48182.

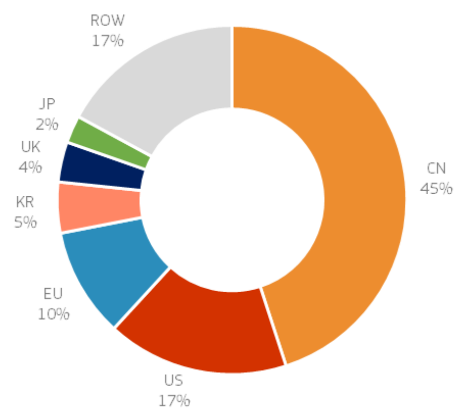
[209] Max Bergmann and Sean Monaghan, "How Supporting Ukraine Is Revitalizing the U.S. Defense Industrial Base," *Center for Strategic and International Studies*, March 2024, https://www.csis.org/analysis/how-supporting-ukraine-revitalizing-us-defense-industrial-base.

Appendix D: AM Technologies

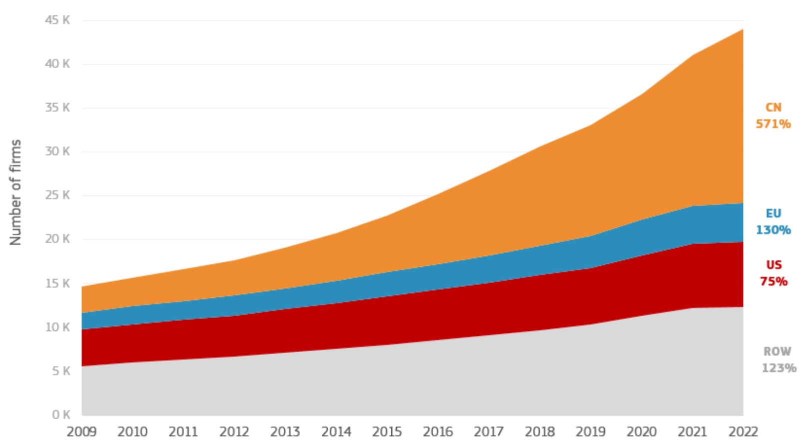
Introduction

AM technologies are crucial to the national security and technological dominance of the United States. They enable innovative capabilities for the warfighter that sustain and strengthen U.S. preeminence over our adversaries.[210] The U.S. National Science and Technology Council defines AM as the innovation of improved methods for manufacturing existing products and the production of new products enabled by advanced technologies."[211] Cheaper sensors and exponential improvements in computational capacity have fueled this integration of machines, networks, sensors, and computational power. Key AM technologies include ADMAN, advanced materials, industrial AI, robotics, the IoT, digital threads, accelerated computing, advanced M&S, and augmented/virtual reality.[212]

Globally, 44,100 firms use AM, with 72% located in China, the U.S., and the EU (see Figure 1). China leads with 44% of these firms and overtook the U.S. as the global AM leader in 2014 (see Figure 2). From 2009 to 2022, Chinese AM firms increased 6.7 times, while EU and U.S. firms grew by 130% and 75%, respectively.[213]



Share of Advanced Manufacturing Firms by Region[214]



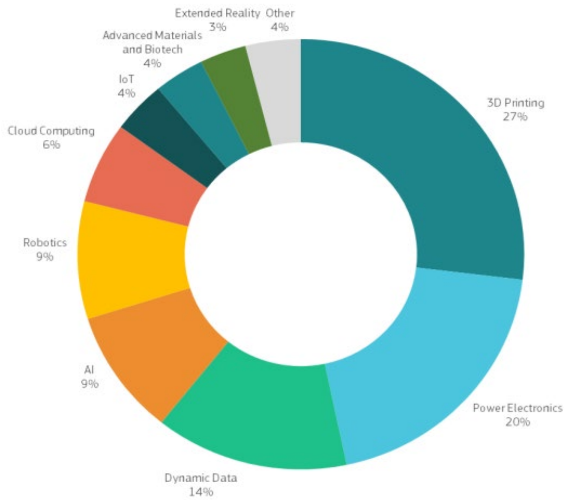
Growth of Advanced Manufacturing by Region[215]

Additive Manufacturing

ADMAN builds objects one layer at a time, minimizing material waste. 3-D printing, creating three-dimensional objects using computer-aided design (CAD), is the most widespread ADMAN method. This approach contrasts with traditional subtractive manufacturing, which

[210] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 4.
[211] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 2.
[212] Helwig and Goldman, *National Action Plan*, 5.
[213] Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 13.
[214] Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 14.
[215] Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 14.

removes material to create parts. ADMAN enables the production of complex geometries that would be difficult or impossible to achieve through conventional methods. The technology has evolved from its beginnings in the 1980s—originating with Hideo Kodama in Japan and parallel developments in the United States—where it was primarily used for rapid prototyping, into a major production methodology. Early systems used ultraviolet-hardened resin, laser-fused powder, or extruded liquid filament. These three technologies form the basis of ADMAN technologies.



Global Advanced Manufacturing Activities by Technology Domain[218]

From 1990 to 2010, many companies experimented with these different technologies. The first commercial 3-D printer debuted in 2006, complemented by the rise of CAD software. This complimentary technology allowed people to create designs on their computer and print them using the new ADMAN techniques. Early 3-D printers were hard to use, and printed objects required significant post-processing.[216] Still, innovation continued, and today, 3-D printing is the largest sector in AM, making up 27% of AM globally (see Figure 3).[217]

ADMAN is the leading additive manufacturing (AM) technology in the United States (40%), the EU (39%), and China (29%) (see Figure 4).[219] The U.S. and EU hold a comparative advantage over China, particularly in technological sophistication and market activity share. In 2022, the U.S. ADMAN market was valued at $3.56 billion and is projected to grow at an annual rate of 21.3% through 2030.[220] U.S.-developed and sold hardware represented 64% of the 2022 market.[221] Adoption has been driven primarily by rapid prototyping in the healthcare, automotive, and aerospace/defense sectors. However, SMM have been slower in adopting the technology due to high costs and regulatory hurdles, highlighting a significant growth opportunity within this market segment.

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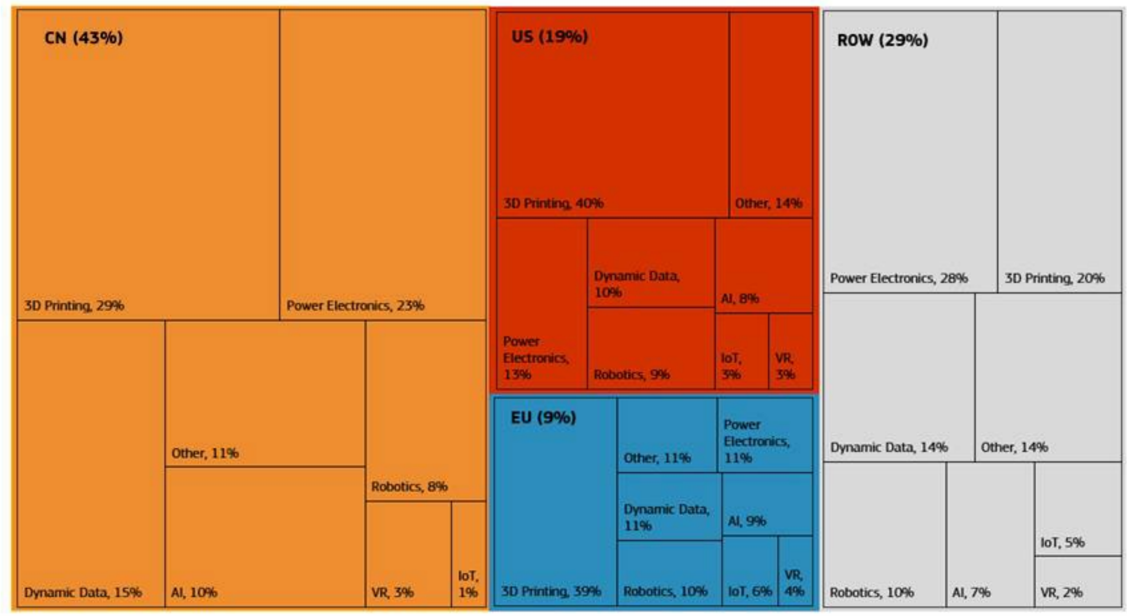
216 Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 15.
217 Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 15.
218 Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 16.
219 "U.S. Additive Manufacturing Market Size, Share Report, 2030," *Grand View Research*, accessed April 23, 2025, https://www.grandviewresearch.com/industry-analysis/us-additive-manufacturing-market-report.
220 "U.S. Additive Manufacturing Market Size, Share Report, 2030," *Grand View Research*.
221 Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 16.



Technology Composition of Advanced Manufacturing in China, the United States, and the European Union[222]

Carbon Printer[223]

Research in innovative new technologies and materials has expanded applications for ADMAN, such as U.S.-designed Carbon 3-D printers (see Figure 5) that use a novel technique, creating an oxygen layer to prevent pieces from adhering to the glass printing surface, while still allowing pieces to be printed rapidly. These technologies now support custom-fitted products like helmets, bike seats, and dental appliances.[224] For example, Carbon 3-D printers have changed the nature of dental dentures; dentists can now digitally scan a patient's mouth and 3-D print dentures all in their office, reducing the number of office visits for the patients from seven to two.[225]

In defense applications, ADMAN has proven particularly valuable for producing spare parts for legacy systems, reducing lead times from months to days. During a visit to Northrop Grumman Space Systems, representatives described how additive manufacturing allowed them to consolidate a component from four separate parts into a single piece, reducing both production time and supply chain complexity.[226] The technology is also used to create tooling and fixtures for conventional manufacturing processes, significantly reducing costs and lead times. Major U.S. defense contractors, like Northrop Grumman, have fully embraced ADMAN.

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[222] Fabiani et al., *Strategic Insights into the EU's Advanced Manufacturing Industry*, 16.
[223] "Expanding the Space of What's Possible with the M3 Series," *Carbon* (blog), accessed May 8, 2025, https://www.carbon3d.com/products/m3-3d-printer.
[224] Industry Site Visit, April 1, 2025.
[225] Industry Site Visit, April 1, 2025.
[226] Industry Site Visit, March 27, 2025.

Despite its advantages, ADMAN faces implementation challenges. Key adoption challenges include high software costs and government regulatory approvals. For instance, Northrop Grumman, like others, uses digital design tools to develop new products, which are compatible with ADMAN processes. The high cost of digital design tools required for ADMAN creates barriers for SMM attempting to integrate this technology into their operations, limiting Northrop Grumman's ability to scale and streamline production across their suppliers. Moreover, material limitations, consistency concerns, and quality control issues can impede adoption, particularly for critical defense applications. While visiting GE Aerospace, researchers noted that the qualification and certification process for additively manufactured parts remains a significant hurdle.[227] The future of ADMAN points toward multi-material printing, higher-precision processes, and integration with other advanced manufacturing technologies. Researchers at the Institute for Advanced Composites Manufacturing Innovation are developing hybrid processes that combine additive techniques with traditional manufacturing methods to optimize both performance and production efficiency.[228] As commercial space increasingly integrates ADMAN, the government must accelerate its part qualification processes for defense systems to facilitate broader use and enable wide-scale adoption.[229] ADMAN is expected to move beyond specialized applications to become a mainstream production methodology across multiple industries.

In France, ADMAN is valued at $2.245 billion (30% of the EU market), with primary aerospace, defense, and space applications. The ADMAN market is expected to grow by 8% over the next few years.[230] French firms prioritize sustainable materials, such as bio-based, recycled, and biodegradable materials, due to strict EU regulations.[231] Yet, during the industry study visit, French aerospace and defense companies did not broadly discuss integrating ADMAN into manufacturing.[232]

Artist Depiction of Yangqu Dam **Error! Bookmark not defined.**

In China, the $1.44 billion ADMAN market is the fastest growing in Asia, projected to expand by 27.5% annually and accounting for 7.1% of the global ADMAN market in 2023. The largest and fastest-growing segment of the Chinese market is manufacturing printers, with a revenue share of 64.59%.[233] Government support and the

[227] Industry Site Visit, March 7, 2025.
[228] Industry Site Visit, February 6, 2025.
[229] Industry Site Visit, March 27, 2025.
[230] "France – Additive Manufacturing (AM)," *U.S. Commercial Service*, U.S. Embassy Paris, last modified August 1, 2024, https://www.trade.gov/country-commercial-guides/france-additive-manufacturing-am.
[231] "France – Additive Manufacturing (AM)," *U.S. Commercial Service*.
[232] "France – Additive Manufacturing (AM)," *U.S. Commercial Service*.
[233] "China Additive Manufacturing Market Size & Outlook, 2030," *Grand View Research*, accessed April 23, 2025, https://www.grandviewresearch.com/horizon/outlook/additive-manufacturing-market/china.

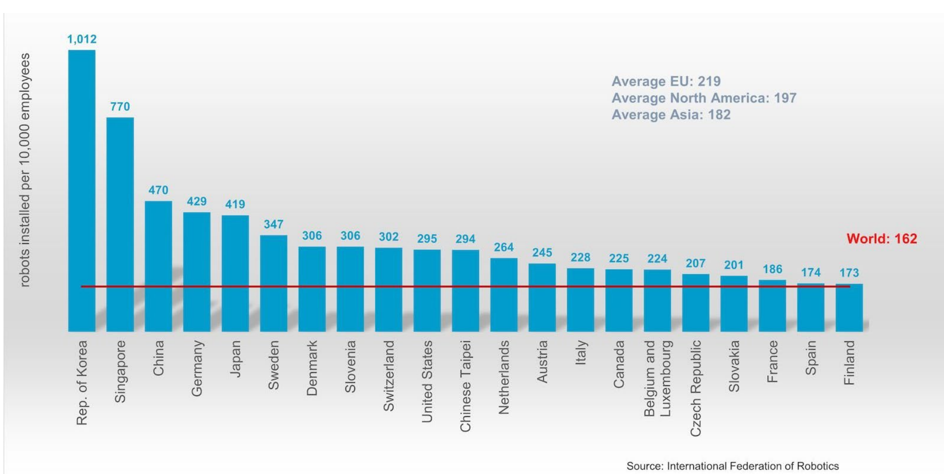
absence of regulatory hurdles allow ambitious projects like the 180-meter 3-D printed Yangqu Dam to proceed.[234]

AI and Robotics in Manufacturing

AI is transforming manufacturing, shifting from human decision-making supported by machines to machines making decisions guided by humans. AI enables automated pattern recognition, complex real-time optimization through sensor-enabled feedback loops, and intricate decision-making functions that fundamentally augment or replace human capabilities.[235] In manufacturing environments, AI applications include predictive maintenance to minimize downtime, adaptive scheduling to optimize production flow, quality assurance through computer vision, and autonomous optimization of manufacturing processes. When combined with robotics, AI enables unprecedented levels of automation and flexibility. While one robot to accomplish many tasks is still not expected until the 2030s, single-function robotics powered by AI continues to see incremental advancements.[236]

The first industrial robots appeared in the 1930s but took off with the advent of computers in the 1960s. Since then, the use of robots and their capabilities have continued to expand. In the 1970s, around 200 industrial robots were used in America. By 2015, there were 1.6 million industrial robots in use in America, and by 2022, 3 million industrial robots were in use worldwide.

Robotics ensures consistency, enhances safety, and boosts efficiency, but remains expensive and underutilized by SMM due to limited technical understanding of where and how they can be used within their manufacturing process.[237] Robots repeat steps identically, ensuring objects are made uniformly. Big data and the IoT allow information to be captured on every robot's inputs, actions, and outputs, giving manufacturers more control over quality, maintenance, and productivity.[238] Industrial robots increase efficiency, improve quality, health, and safety conditions for workers, work longer hours than humans, and can increase profitability.



Robot Density in the Manufacturing Industry in 2023

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[234] Petridou, "AI and 3D Printers Build 180-Meter-Tall Dam."

[235] Matthew Finio and Amanda Downie, "How Is AI Being Used in Manufacturing?," *IBM Think*, November 15, 2024, https://www.ibm.com/think/topics/ai-in-manufacturing.

[236] Messina, *Research Opportunities for Advancing Measurement Science*, 2024.

[237] "The Future of Robotics and Automation in Manufacturing," *Plex Systems*, accessed April 24, 2025, https://www.plex.com/knowledge-articles/mes/future-robotics-and-automation.

[238] Drew Turney, "History of Industrial Robots: Complete Timeline from 1930s," *Autodesk Design & Make*, August 12, 2022, https://www.autodesk.com/design-make/articles/history-of-industrial-robots.

The U.S. deploys 295 robots per 10,000 manufacturing employees, ranking 10th globally. (see Figure 7).[239] Most robots today are used in the automotive and electronics industries, typically carrying out rigid, repetitive tasks. However, U.S. researchers are advancing the field by developing AI-enabled robots capable of human-like dexterity. Teams from institutions such as California State University-Northridge and the University of Wisconsin-Madison are collaborating to train robots using AI to perform a broader range of motions that closely mimic human movement. Their objective is to enable robots not only to execute tasks but also to perceive and understand their actions, allowing them to take on more complex and less repetitive work with high precision. To achieve this, the team is building a four-layer robotic "brain" consisting of a knowledge layer, a generative solution layer, an operational layer, and a cognitive layer. Combined, these layers will empower the machine with agency, allowing it to reason, act, and reflect.[240]

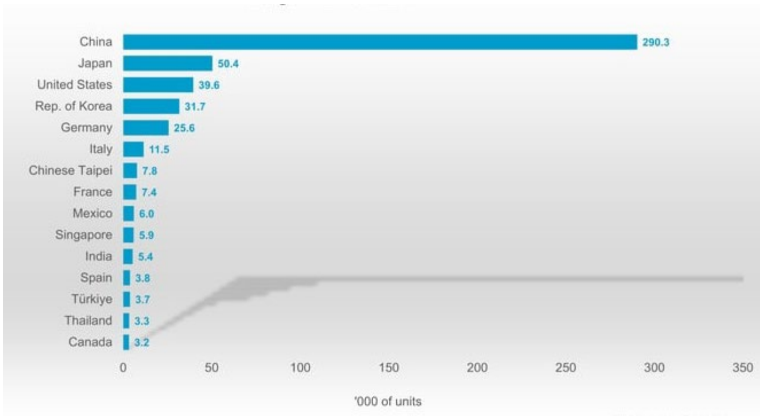
Today, automation is mainly used in repetitive tasks with high volume and low mix. In industries like defense production, with low volume and high mix, robotics is used in production steps that are dirty, dangerous, and dull. Defense applications of AI and robotics include automated inspection of critical components, adaptive production lines for variable batch sizes, and autonomous logistics systems. During a visit to Northrop Grumman's Rolling Meadows facility, representatives described how they automated the final step in sensor assembly, where small screws must be inserted at a specific torque, a process that previously caused repetitive stress injuries among workers.[241] Northrop Grumman also discussed their use of automation in paint applications, where government regulations limit how long a human can perform the function.[34] By automating these steps, Northrop Grumman completes the work faster and avoids harmful exposure to its workforce [242]

Implementation challenges include workforce acceptance, cybersecurity concerns, and the substantial investment required for both hardware and software components. According to a 2024 survey by the Manufacturing Leadership Council, only 51.6% of manufacturers have a corporate AI strategy.[243] Additionally, the physical-virtual nature of AI-driven systems creates unique security requirements, as digital vulnerabilities could compromise physical manufacturing systems. Companies like GAM Enterprises help manufacturers incorporate automation. GAM designs and manufactures components to automate manufacturing equipment, working with manufacturers to design specifically for their needs.[244]

EU countries average 219 robots per 10,000 employees, with Germany, Sweden, Denmark, and Slovenia all in the top ten countries globally. Specifically, France averages 186 robots per 10,000 employees, ranking 19th globally (see Figure 7).[245] The primary industries using robotics are automotive, metal products, and plastics. The BMW Group in Munich, Germany, is testing humanoid robots in its Spartanburg, South Carolina, plant. In the latest test, a robot built by Figure, a California company, successfully inserted sheet metal parts into specific fixtures. This production step required the robot to be particularly dexterous. BMW targeted this step for

239 International Federation of Robotics, "Global Robot Density in Factories."
240 Patrick Tucker, "Could This Breakthrough in Robot Manufacturing Reshape Warfare?," *Defense One*, April 14, 2025.
241 Industry Site Visit, April 2, 2025.
242 Industry Site Visit, April 2, 2025.
243 Deloitte Research Center for Energy & Industrials, *2025 Manufacturing Industry Outlook*, 4.
244 Industry Site Visit, April 4, 2025.
245 International Federation of Robotics, "Global Robot Density in Factories."

automation because it is an ergonomically awkward and tiring task for employees.[246] KNDS, a French munitions manufacturer, has incorporated automation into its artillery production lines. When deciding where to invest in automation, KNDS targets production steps that are dangerous or ergonomically challenging for workers to perform repetitively.[247]



Annual Installations of Industrial Robots by Country

China averages 470 robots per 10,000 employees, ranking third globally and recently surpassing Germany and Japan in 2023.[248] China leads the world in industrial robot installations, with 290,300 robots installed in 2023, 5.8 times more than the next country, Japan. China is aggressively modernizing its production with the help of federal subsidies. Domestic and international robot suppliers have established production plants in China to feed this growth.[249] Made in China 2025 set the goal of ending China's reliance on global technology and upgrading its industrial capability and smart manufacturing. The plan identified automated machine tools and robotics as one of 10 key industries, and set the goal of 50% domestic market share for Chinese industrial robots by 2020 and 70% market share by 2025.[250] On December 28, 2021, China's Ministry of Industry and Information Technology released "The five-year development plan for the robotics industry in the 14th Five-year." The plan states that during the 14th five-year period (2022-2027), the industry should focus on developing high-end and intelligent technologies centering around five main tasks: (1) improving innovation capabilities, (2) building a solid foundation for industrial development, (3) increasing the supply of high-end products, (4) expanding the depth and breadth of applications, and (5) optimizing the overall structure of the robotics industry.[251]

[246] "Successful Test of Humanoid Robots at BMW Group Plant Spartanburg," *BMW Group PressClub*, August 6, 2024, https://www.press.bmwgroup.com/global/article/detail/T0444265EN/successful-test-of-humanoid-robots-at-bmw-group-plant-spartanburg?language=en.
[247] Industry Site Visit, April 9, 2025.
[248] International Federation of Robotics, "Global Robot Density in Factories."
[249] International Federation of Robotics, "World Robotics 2023 Report: Asia Ahead of Europe and the Americas," *International Federation of Robotics*, accessed April 24, 2025, https://ifr.org/ifr-press-releases/news/world-robotics-2023-report-asia-ahead-of-europe-and-the-americas.
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Digital Threads & Advanced M&S

A digital thread integrates data and provides a virtual representation of a product's entire lifecycle—from design, through manufacturing, sustainment, and end-of-life management.[252] Its primary function is to gather and analyze data across all stages of the process, providing a comprehensive view of manufacturing systems to support informed decision-making. Digital threads integrate technologies such as product lifecycle management systems and IoT sensors to enable this connectivity. By implementing digital threads, manufacturers can enhance operational agility, improve collaboration across departments, streamline product development, and ensure compliance with regulatory standards.[253] The digital thread market is currently valued at $12.04 billion and is expected to grow at an annual rate of 21.9% through 2034.[254]

Implementation maturity ranges from stand-alone digital models to advanced systems integrating real-time sensor data that predict failures and optimize processes. Most manufacturers currently utilize only 1-5% of collected data effectively, representing a substantial opportunity to optimize production processes.[255] The ability to create virtual models that precisely replicate physical assets enables manufacturers to simulate different operating conditions, predict maintenance needs, and optimize performance without disrupting actual production. Advanced M&S leverages sophisticated models to represent complex systems and processes, allowing developers and manufacturers to analyze and predict system behavior under a range of conditions. This capability helps manufacturers gain deeper insights into their operations, identify bottlenecks, and uncover opportunities for automation. One prominent form of advanced M&S is the digital twin, a complete digital replica of a product used to design and refine manufacturing processes. Many companies use M&S to virtually test production lines, detect potential issues, and make necessary adjustments before committing to physical hardware investments.

As manufacturing systems become increasingly interconnected, the industry has become a prime target for cyberattacks. Since 2021, manufacturing has ranked as the most frequently attacked sector, with ransomware accounting for 23% of incidents.[256] In response, technologies are evolving to embed cybersecurity protocols directly into digital threads. Emerging solutions also incorporate AI and machine learning to analyze data throughout the digital thread, enabling predictive insights. Additionally, the adoption of open standards is improving integration across the supply chain, enhancing both security and operational efficiency.

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[252] Tasnim A. Abdel-Aty and Elisa Negri, "Conceptualizing the Digital Thread for Smart Manufacturing: A Systematic Literature Review," *Journal of Intelligent Manufacturing* 35 (2024): 3646.

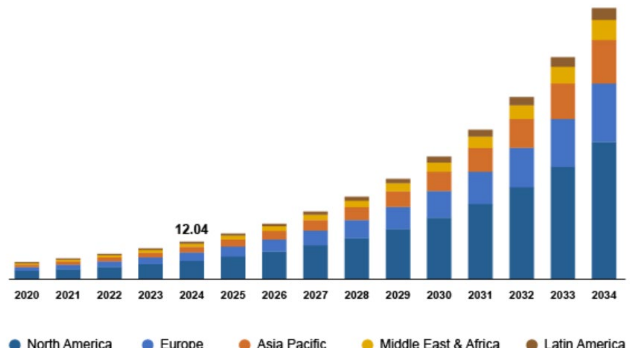
[253] Chrystal China, "Digital Twin vs. Digital Thread: What's the Difference?," *IBM Think*, June 29, 2023, https://www.ibm.com/think/topics/digital-thread-vs-digital-twin.

[254] Polaris Market Research & Consulting LLP, "Digital Thread Market to Reach USD 87.01 Billion By 2034, at a 21.9% CAGR by 2034 | PMR," *GlobeNewswire News Room*, December 19, 2024, https://www.globenewswire.com/news-release/2024/12/19/2999614/0/en/Digital-Thread-Market-to-Reach-USD-87-01-Billion-By-2034-at-a-21-9-CAGR-by-2034-PMR.html.

[255] Abhinav Chugh et al., *Advanced Manufacturing Strategic Intelligence Briefing* (Geneva: World Economic Forum, February 21, 2025), 8.

[256] Industry Site Visit, April 3, 2025.

The United States is a global leader in AI and digital technologies, with North America holding the largest digital thread market revenue share in 2024 (see Figure 9).[257] The 2022 National Strategy for ADMAN emphasizes digital technologies as a key objective, specifically highlighting three priorities: (1) digital manufacturing, (2) the use of AI in manufacturing, and (3) cybersecurity. [258]



Digital Thread Market by Region

Many SMMs are beginning to adopt digital thread technologies. For example, Arc-Tronics, a family-owned printed circuit board assembly company, implemented a digital inventory management system that automatically identifies, labels, and stores inventory. This system provides real-time inventory visibility, preventing production delays caused by missing parts. It also verifies that the correct components are loaded at each assembly stage, improving overall product quality. While Arc-Tronics now sees clear benefits from this digital integration, the company initially adopted the system to improve storage efficiency after seeing it at an industry trade show.[259] Their experience illustrates the need for greater education on the broader advantages of digital thread adoption.

Larger technology providers like Oracle offer comprehensive digital solutions for manufacturers, covering functions such as hiring, workforce training, inventory management, logistics, and shipping. Although these systems are advanced and robust, they often come with high costs and fail to deliver their full return on investment because companies do not fully leverage their capabilities.[260]

In defense applications, digital twins have proven valuable for sustaining legacy systems where original manufacturers may no longer exist. The Navy's Additive Manufacturing Center of Excellence has successfully used digital twins to model and print over twenty critical components for installation on in-service submarines.[261] Similarly, at Oak Ridge National Laboratory's Manufacturing Demonstration Facility, researchers have demonstrated how digital twin technology can replicate complex systems like blast furnaces to optimize operations and train workers in virtual environments before they encounter actual equipment.[262]

Industry 4.0, originating in Germany, has become industry speak for intelligent, networked manufacturing. Germany leads Europe by co-locating research institutions with manufacturers in clusters to promote digitalization.[263.] Conversely, France lags, with little apparent adoption among

[257] Polaris Market Research & Consulting LLP, "Digital Thread Market to Reach USD 87.01 Billion By 2034, at a 21.9% CAGR by 2034 | PMR," *GlobeNewswire News Room*, December 19, 2024, https://www.globenewswire.com/news-release/2024/12/19/2999614/0/en/Digital-Thread-Market-to-Reach-USD-87-01-Billion-By-2034-at-a-21-9-CAGR-by-2034-PMR.html.

[258] National Science and Technology Council, *National Strategy for Advanced Manufacturing*, 10-11.

[259] Industry Site Visit, April 4, 2025.

[260] Industry Site Visit, April 2, 2025.

[261] U.S. Department of Defense, *National Defense Industrial Strategy Implementation Plan for FY2025* (Washington, DC: Office of the Assistant Secretary of Defense for Industrial Base Policy, November 21, 2024), 16, https://www.businessdefense.gov/docs/ndis/NDIS%20Implementation%20Plan_Revised_03182025_508.pdf.

[262] MxD, "How Digital Twin Technology—and a Virtual Blast Furnace."

[263] Germany Trade & Invest, "Germany – The World's Leading Industrie 4.0," *Germany Trade & Invest*, accessed April 24, 2025, https://www.gtai.de/en/invest/industries/industrial-production/industrie-4-0.

leading defense firms, with no discussion of digital threads or M&S during the industry study visit. Recognizing the French and EU lag, initiatives like DIGITALEUROPE aim to bridge this gap and encourage the integration of digital technologies.[264]

Like the United States, China has faced challenges in encouraging domestic firms to adopt digital technologies. Currently, only 37% of Chinese manufacturers have implemented basic digitalization and industrial intelligence, and just 4% use advanced, cutting-edge technologies.[265] However, China's digital transformation market is expanding, largely driven by government initiatives like the Made in China 2025 plan and targeted subsidies. Chinese technology firms like Alibaba and Huawei play a central role in this effort. By expanding access to scalable computing resources, advanced analytics, and 5G technology, these companies are helping lower the barriers to digital adoption across the manufacturing sector.[266]

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[264] Ray Pinto, "DIGITALEUROPE's Declaration to Ensure the EU Is a World Leader in Digital Manufacturing," *DIGITALEUROPE* (blog), accessed April 24, 2025, https://www.digitaleurope.org/resources/digitaleuropes-declaration-to-ensure-the-eu-is-a-world-leader-in-digital-manufacturing/.

[265] Helwig and Goldman, "National Action Plan," 12.

[266] Research and Markets, "The Digital Transformation Market in China, Forecast to 2029: Trends, Demand Drivers, Challenges, and Emerging Opportunities," *GlobeNewswire News Room*, December 27, 2024, https://www.globenewswire.com/news-release/2024/12/27/3002160/28124/en/The-Digital-Transformation-Market-in-China-Forecast-to-2029-Trends-Demand-Drivers-Challenges-and-Emerging-Opportunities.html.

Appendix E: U.S. AM Policies

1. National Strategy for Advanced Manufacturing

Latest Version: October 2022

Lead Agency: National Science and Technology Council, Office of Science and Technology Policy

Description:

- A national framework that outlines priorities to strengthen U.S. leadership in AM.
- Promotes technology development, workforce skills, resilient supply chains, and sustainability

2. Manufacturing USA (National Network for Manufacturing Innovation)

Established: Executive Order 13629 (2012), formalized by the Revitalizing American Manufacturing and Innovation Act of 2014– Public Law 113-235, Title VII

Description:

- A network of 17 public-private manufacturing innovation institutes.
- Each focuses on a key technology (e.g., ADMAN, robotics, digital thread).
- The goal is to bridge the gap between early research and production.

3. CHIPS and Science Act of 2022 – Public Law 117-167

Signed into Law: August 9, 2022

Lead Agencies: DOC, National Science Foundation, DOE

Description:

- Provides $52 billion for semiconductor manufacturing.
- Authorizes $170 billion for broader research and technology initiatives, including manufacturing hubs, workforce development, and innovation ecosystems.

4. Executive Order 13806 (2017) – Assessing and Strengthening the Manufacturing and Defense Industrial Base

Signed: July 21, 2017

Lead Agency: DoD (via Office of Industrial Policy)

Description:

- Mandated a comprehensive assessment of the U.S. manufacturing and defense industrial base.
- Identified key vulnerabilities in machine tools, microelectronics, rare earths, and the workforce.

5. Executive Order 14017 (2021) – America's Supply Chains

Signed: February 24, 2021
Lead Agency: White House + interagency effort

Description:

- Ordered 100-day reviews of key critical supply chains (semiconductors, rare earths, batteries, pharmaceuticals).
- Long-term objective is to reduce foreign dependency and strengthen domestic manufacturing capacity.

6. National Defense Industrial Strategy

Released by: DoD, January 2024
Lead Office: Office of the Assistant Secretary of Defense for Industrial Base Policy

Description:

- A strategic roadmap to modernize the defense industrial base with a strong emphasis on advanced manufacturing.
- Promotes agile production, dual-use technology adoption, and public-private partnerships.

7. DOE AM Office

Agency: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

Description:

- Supports R&D in energy-efficient manufacturing, smart manufacturing, and next-generation materials.
- Funds national labs, industry consortia, and small business collaborations.

8. National Science Foundation AM Programs

Agency: National Science Foundation

Description:

- Supports research on future manufacturing systems, cyber-physical systems, and bio/eco manufacturing.
- Provides grants to universities, research centers, and innovation hubs.

9. Small Business Innovation Research and Small Business Technology Transfer

Lead Agencies: Multiple (DoD, DOE, National Science Foundation, National Aeronautics and Space Administration, etc.)

Description:

- Provides funding to small businesses to commercialize innovative technologies, including advanced manufacturing.
- Often used as an on-ramp for non-traditional firms in defense and aerospace.

10. SelectUSA – Manufacturing Investment Promotion

Lead Agency: DOC

Description:

- Encourages foreign and domestic investment in U.S. manufacturing clusters.
- Supports reshoring and strategic sectors like photonics, robotics, aerospace, and electronics.

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