Science 6 December 2013:
Vol. 342 no. 6163 pp. 1173-1175
DOI: 10.1126/science.1242210
• POLICY FORUM
TECHNOLOGY

Advanced Manufacturing Policies and Paradigms for Innovation

William B. Bonvillian*

Author Affiliations
*Director, Washington Office, Massachusetts Institute of Technology, Washington, DC 20002, USA.
E-mail: bonvill@mit.edu

Science Magazine

Manufacturing in the United States is usually not pictured as part of the innovation process. This is a fragmented, disconnected view; innovation demands to be looked at as a system, from early-stage research through production. In contrast, Germany has a culture of engineering and Japan of artisanship and quality that embrace histories of production innovation and manufacturing success. Both nations have higher-wage and higher-cost manufacturing sectors than the United States, yet they have run major trade surpluses in manufactured goods, whereas the United States has run large deficits (1, 2).

Can the United States reinvigorate its manufacturing sector? Government and industry are exploring “advanced manufacturing” (AM): innovative manufacturing technologies and related processes that can grow productivity, speed product development, and customize products to offset higher wages and costs [pp. 155-161 (3)]. The White House has formed the Advanced Manufacturing Partnership (AMP) with industry and universities to work on production innovation and policy (4), federal R&D agencies are developing AM agendas (5), numerous reports have been produced [e.g., p. 6 in (3)], and legislation is being developed in Congress (6). The U.S. case could offer lessons for other developed nations that give priority to their service economies; strengthened U.S. production models could benefit many nations. Other developed nations with high-cost manufacturing are exploring AM as well, led by Germany and the United Kingdom, and China has a comparable "Strategic Emerging Industries" plan to secure production leadership (7–9).

Production in the U.S. Innovation System

Much innovation occurs in the production stage. Moving from prototype to product can take years. It requires solving engineering design problems, overcoming production and component cost problems, building production processes, creating an efficient production system, developing and applying new production and product business models, educating a workforce, building a supply chain, financing scale up, actually scaling up production to fit evolving market conditions, and reducing all these steps to a routine. The initial innovation is often thoroughly reworked. These are highly creative elements needed at the outset of production at scale, requiring much science and engineering at nearly every point. The research-to-prototype stages begin the innovation process, but the pre- and outset-of-production stages are also vital. These stages are critical for incremental technology advance, as well as for breakthrough and radical technology innovation.

Despite manufacturing strength in the 19th and early 20th centuries, U.S. innovation since World War II and the Cold War has become front-end loaded, largely focused on early-stage research and development (R&D). If an innovation system must also encompass the back end—the prototype, demonstration, test-bed, and initial production phases—the United States has a gap (10). China, which has passed the United States in manufacturing net output, is focused on the back end of innovation, particularly production, as it works to build its front-end R&D system. Although many have assumed China achieved production leadership through lower wages and costs, recent work suggests it is able to rapidly scale up production volume through advanced processes that are integrated across regional firms and tied to system efficiencies and cost savings [pp. 121—154 in (3); (11, 12)].

One part of the U.S. innovation system—the defense sector—has worked at both the front and back ends, undertaking R&D; prototyping; demonstration; test beds; and, through product procurement, often initial market creation. This system (13) jump-started key innovation waves of the 20th century: aviation, electronics, space, computing, and the Internet (14). With the decline in defense procurement and R&D support in the post-Cold War era, this innovation role has become less central (15).

Decline in U.S. production capability is increasingly apparent (16-19). Manufacturing employment fell by 31% between 2000 and 2010. Some have argued that this is due to productivity gains, but recent data do not bear this out. Output fell in this period in 16 of the 19 manufacturing sectors per government data measures, and output appears overstated in the remaining sectors. Because output is a key factor in productivity, manufacturing productivity appears substantially lower than we have been assuming; therefore, there are other structural causes of the deep manufacturing job losses. This is reflected in investment data: Manufacturing fixed-capital plant investment declined in 15 of 19 measured industrial sectors in this decade. Recent data suggest that an uptick in U.S. production employment is part of the slow economic recovery, but the numbers are modest, not close to overtaking the size of the decline (20). Yet manufacturing remains crucial: Industrial firms are at the core of the innovation talent system, employing 64% of scientists and engineers and performing 70% of private sector R&D (21).

Innovate (T)Here and Produce (T)Here?

Since World War II, the U.S. economy has been organized around world leadership in technology. It developed a comparative advantage over other nations in innovation and, as a result, led nearly all the significant innovation waves of the 20th century. The operating assumption was that the United States would innovate and translate those innovations into products. By innovating here and producing here, it would realize the full range of economic gains from innovation at all the stages, from research and development through production at scale, and the follow-on life cycle of the product. It worked—the United States became the world's richest economy.

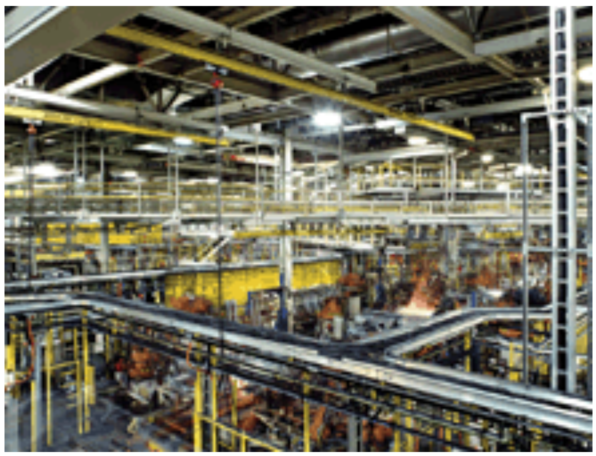
The United States since 1940 has been playing out economic growth theory—that the predominant factor in economic growth is technological and related innovation (22)—and demonstrating that it works, with its model increasingly emulated abroad. But in recent years, with the advent of a global economy, the innovate-here-and-produce-here model is breaking down. In some industrial sectors, firms can now sever R&D and design from production. Codable information technology (IT)-based specifications for goods that tie to software-controlled production equipment have enabled “distributed” manufacturing (23). Now the innovate-here-and-produce-there model appears to work well for many IT and commodity products.

However, there appear to be many sectors where the distributed model does not work and that still require a close connection between research, design, and production, e.g., capital goods, aerospace products, energy equipment, and complex pharmaceuticals. Here, the production infrastructure provides constant feedback to the R&D and/or design phases. Product innovation is most efficient when tied to a close understanding of and linkage to manufacturing processes. However, if R&D/design and production are tightly linked, these innovation stages may have to follow production offshore. Produce-here-and-innovate-there may be even more disruptive than innovate-here-and-produce-there. This brings the foundations of U.S. innovation-based economic success into question. If federal R&D investments, for example, no longer translate as well into U.S. economic growth, innovation support may erode.

Paradigms for Manufacturing Innovation

If technological and related innovation is the core factor in economic growth, this points toward an innovation-oriented strategy in production. Although industry has been discussing macro factors in manufacturing recovery—tax, trade, currency valuation, and regulation—there are structural factors in the manufacturing innovation system that require focus. If production turns out to be important to the health of the overall innovation system because the two are interdependent, we have a systems problem not simply a macro policy problem. What could be undertaken?

Historically, manufacturing leadership has depended on leading new technology “paradigms” and combining these with new process and business models to support them. This was the road map for Britain's leadership of the industrial revolution built around the steam engine and textile machinery (24), for America's leadership in the 19th century through interchangeable machine-made parts and mass production capability (25), and for Japan's consumer electronics and auto leadership in the 1970s–80s through quality production (26). The United States will not be interested in competing with low-cost, low-wage, increasingly innovative emerging nations by slashing its wage base, so it must improve its productivity and efficiency to be cost-competitive. There appear to be new manufacturing “paradigms” at hand, discussed below, that could play roles in transforming production (27). The willingness of numerous industries to compete for and share the costs of federal investments in AM areas indicates that these are well past the speculative stage.



“Network-centric” production. Embed IT advances throughout manufacturing value chains, including a mix of advanced IT, radio-frequency identification tags, and sensors, so that each element in the production process becomes “smart,” to optimize efficiencies from resource through production through product life cycle. Use new decision-making tools from “big data” analytics, with advanced robotics, supercomputing, and advanced simulation and modeling. The cost and complexity of software, a major component in complex products, is an inhibitor in efficient production. Integrating software development at the outset with design, as well as new systems for hardware and software integration, appears to be key.

Advanced materials. Create a “materials genome,” using supercomputing to design all possible materials with designer features, then fit new materials precisely to product needs for strength, flexibility, weight, and production cost. Evolve new biomaterials from synthetic biology. Explore biofabrication and “lightweight everything.”

Nanomanufacturing. Fabricate at the nano scale. Embed nano-features into products to raise efficiency and performance.

Mass customization. Produce one or small lots at the cost of mass production—for example, through three-dimensional printing and additive manufacturing, where products can be fabricated in highly complex forms through printing from powders as opposed to traditional machine-tool processes.

Distribution efficiency. Driving even 10% out of the cost of product distribution can shift decisions on whether to produce in the United States or abroad. Further IT advances that yield distribution efficiencies, including in the supply chain, could yield this.

Energy efficiency. Excess energy is “waste,” a nonrecoverable production cost. U.S. manufacturing has long been overly energy-intensive. Energy-efficiency technologies and processes, such as through power electronics, could significantly drive down production costs.

Filling the Gaps

If the United States needs new production paradigms, there are gaps that must be filled in the innovation system to realize them. First, U.S. R&D remains strong, but lacks an R&D effort organized around AM challenges (28). Most of the potential paradigms need R&D input, but both R&D and implementation also require corresponding technology strategies developed by industry, government, and university experts, to fill a second gap. These strategies would identify the AM technology opportunities, the R&D to get there, the collaborative process required, and design the test bed for implementation, as a prelude to more in-depth ongoing technology road-mapping processes. In addition to manufacturing R&D tied to a collaborative technology strategy, “manufacturing institutes,” recommended by the AMP report, could fill a third gap (27). One institute, an industry-university consortium around additive manufacturing (29), has now started. Other institutes, with costs shared between federal agencies, states, and industry, are proposed for digital manufacturing, lightweight materials, and power electronics.

Why institutes? The majority of the U.S. manufacturing sector consists of small and midsize firms that are risk-averse and thinly capitalized; thus, they are not in a position to perform research or adopt new technologies and processes unless the costs and efficiency gains are fully demonstrated and understood. Although larger firms once assisted their supply chains in this role, playing a vertical integration function, in an era of intense global competition, they have often cut back to their core competencies. Therefore, they are less able to assist suppliers and have their own competitive problems adapting. As Massachusetts Institute of Technology's (MIT's) Suzanne Berger puts it, manufacturing firms are “increasingly home alone” [pp. 15–20 in (3), (30)]. Taking a page from Germany's Fraunhofer system [pp. 121–140 in (3)], institutes could act as test beds, providing a range of industries and firms, small and large, with an opportunity to collaborate on, test, and prove prototypes for advanced production technologies and processes.

A fourth gap is talent. How will technical workers and engineers be trained to work with advanced technologies and develop processes and routines so as to introduce them into production systems? The institutes could help in this role, and the Department of Labor recently made awards for a $400 million program that requires community colleges to create online workforce education in AM. A new credentialing system between community colleges and industry organizations for manufacturing skills and development of an AM engineering curriculum could help. Without a workforce fluent with AM, it simply cannot be introduced.

Economy-wide macro policies in trade, tax, and currency valuation will be needed, too. But a focus on the structural problems in the gap-ridden manufacturing innovation system is critical. These initial steps—advanced manufacturing R&D, a strategy for new manufacturing paradigms, collaborative institutes, and training talent—speak to this structural question. The AMP report proposes addressing a number of these gaps (17, 27).

Production is the central way an economy scales growth. Services are largely face-to-face and tend to scale gradually, but production can scale rapidly and enable geometric economic expansion. Firms will also increasingly offer high-value goods tied to services to provide customers with solutions; the tradable good can scale, making the accompanying service tradeable and scaleable as well [pp. 111–114 in (3)]. This means the success of services-dominant economies like the United States increasingly will be linked to success in manufacturing (31). Production is the major enabler of “increasing returns” in an economy (32), a foundational societal wealth creator [pp. 248–270 and 317–319 in (24)]. Unless the United States treats production as a critical element that must be better connected into its innovation system, it risks erosion of that system.

References and Notes

1 ↵ U.S. Bureau of Economic Analysis, U.S. International Trade in

Goods and Services (1992–2012); www.bea.gov/international/index.htm#trade.
2 ↵ Organization for Economic Cooperation and Development, Goods Trade Balance, Trade: Key Tables from OECD, Table 3, 8 January 2013; www.oecd-ilibrary.org/trade/goods-trade-balance_20743920-table2.
3 ↵ S. Berger, MIT Task Force on Production in the Innovation Economy, Making in America (MIT Press, Cambridge, MA, 2013). Google Scholar
4 ↵ About the Advanced Manufacturing Partnership 2.0; www.manufacturing.gov/amp.html.
5 ↵ For example, www1.eere.energy.gov/manufacturing/; www.darpa.mil/Our_Work/TTO/Programs/Adaptive_Vehicle_Make__%28AVM%29.aspx>; and www.manufacturing.gov/agency_partners.html.
6 ↵ S. 1468, H.R. 2996, 1st. Sess. (2013).
7 ↵ Industry 4.0 Working Group, National Academy of Science and Engineering, "Securing the future of German manufacturing: Recommendations for implementing the strategic initiative Industry 4.0" (Sponsored by the Federal Ministry of Education and Research, Bonn, Germany, April 2013).
8 Technology Strategy Board (UK), High Value Manufacturing: Key Technology Area, 2008–11 (TSB, Swindon, UK, 2008); http://webarchive.nationalarchives.gov.uk/20130221185318/www.innovateuk.org/_assets/pdf/corporate-publications/tsb_highvaluemanu.pdf..
9 ↵ S. Shippet al., "Emerging trends in advanced manufacturing" (Paper P-4603, Institute for Defense Analysis, Alexandria, VA, 2012), pp. 68–72; https://www.ida.org/upload/stpi/pdfs/p-4603_final2a.pdf.
10 ↵ W. Bonvillian, Sci. Publ. Policy; 10.1093/scipol/sct059 (2013). Abstract/FREE Full Text
11 ↵ J. Nahm, E. S. Steinfeld, World Dev. **54**, 288 (2014). CrossRefGoogle Scholar
12 ↵ D. Breznitz, M. Murphree, Run of the Red Queen (Yale Univ. Press, New Haven, CT, 2011). Google Scholar
13 ↵ W. Bonvillian, R. Van Atta, ARPA-E and DARPA: Applying the DARPA model to energy innovation. J. Technol. Transf. **36**, 469 (2011). CrossRefGoogle Scholar
14 ↵ V. W. Ruttan, Is War Necessary for Economic

Growth?: Military Procurement and Technology Development (Oxford Univ. Press, New York, 2006). Google Scholar

15 ↵ V. W. Ruttan, Issues Sci. Technol. Online (Winter 2006); www.issues.org/22.2/ruttan.html.

16 ↵ Sources for data in this paragraph are (17), (18); pp. 25–64 in (3); and (19), and sources cited therein.

17 ↵ W. Bonvillian, Innovations **7**, 97 (2012). CrossRefGoogle Scholar

18 ↵ Information Technology and Innovation Foundation, Worse Than the Great Depression (ITIF, Washington, DC, 2012); http://www2.itif.org/2012-american-manufacturing-decline.pdf.

19 ↵ S. Helper, T. Krueger, H. Wial, Why Does Manufacturing Matter? Which Manufacturing Matters? A Policy Framework (Brookings Institution, Washington, DC, 2012). Google Scholar

20 ↵ Bureau of Labor Statistics, Databases, tables and calculations, manufacturing–all employees (2013); http://data.bls.gov/timeseries/CES3000000001?data_tool=XGtable.

21 ↵ G. Tassey, Rationales and mechanisms for revitalizing U.S. manufacturing R&D strategies. J. Technol. Transf. **35**, 283 (2010). CrossRefGoogle Scholar

22 ↵ R. M. Solow, Growth Theory, an Exposition (Oxford Univ. Press, New York, ed. 2, 2000). Google Scholar

23 ↵ S. Berger, How We Compete: What Companies Around the World Are Doing to Make It in Today's Global Economy (Doubleday Currency, New York, 2005), pp. 251–277. Google Scholar

24 ↵ W. Rosen, The Most Powerful Idea in the World, A Story of Steam, Industry, and Invention (Random House, New York, 2010). Google Scholar

25 ↵ C. R. Morris, The Dawn of Innovation: The First American Industrial Revolution (Public Affairs, New York, 2012). Google Scholar

26 ↵ J. Womack, D. Jones, D. Roos, The Machine That Changed the World (Free Press, New York, 1990). Google Scholar

27 ↵ President's Council of Advisors on Science and Technology, "Advanced manufacturing partnership, report to the President on capturing domestic competitive advantage in advanced

manufacturing” (PCAST, Executive Office, Washington, DC, 2012).

28 ↵ D. Breznitz, P. Cowhey, “America's two systems of innovation: Recommendations for policy changes to support innovation, production and job creation” (Connect Innovation Institute, San Diego, CA, 2012), pp. 16–19. Google Scholar

29 ↵ National Additive Manufacturing Innovation Institute, http://namii.org.

30 ↵ MIT Taskforce on innovation and Production, “Preview of the MIT production in the innovation economy report” (MIT Press, Cambridge, MA, 2013), p. 27; http://web.mit.edu/press/images/documents/pie-report.pdf.

31 ↵ OECD, “Science, technology and industry scoreboard 2013” (OECD, Paris, 2013), p. 47.

32 ↵ B. Arthur, Increasing Returns and Path Dependence in the Economy (Univ. of Michigan Press, Ann Arbor, 1994). Google Scholar