William B. Bonvillian

Reinventing American Manufacturing
The Role of Innovation

The American public has become alarmed about the decline of U.S. manufacturing,[1] although most are reluctant to send their sons and daughters to work in factories. Manufacturing work still brings to the public mind such words as "dumb," "dirty," and "dangerous." Some visualize newsreel clips of Ford's famous River Rouge plants in the 1930s, belching dark smoke while predawn crowds of grim, cloth-hatted workers pour through tall factory gates armed with lunch pails. But these are old pictures. The repetitive assembly line has disappeared in modern manufacturing plants, replaced by sophisticated equipment controlled by highly skilled technical workers. A typical advanced plant looks and feels much like the interior of a modern office building, except that it is far quieter, less crowded, and cleaner.

HOLLOWING OUT?

And yet, the U.S. manufacturing sector is in decline.

Employment

Over the past 50 years, manufacturing's share of GDP has shrunk from 27 percent to below 12 percent. For most of this period (1965-2000), the number of manufacturing employees generally remained constant at 17 million, but over the past decade it fell precipitously to just below 12 million, or 31.4 percent.[2] All manufacturing sectors experienced job losses between 2000 and 2010, but the lower value sectors readily subject to globalization, such as textiles and furniture, were most adversely affected, losing almost 70 percent and 50 percent of their jobs, respectively.[3]

Investment

Manufacturing fixed capital investment (plant, equipment, and IT) grew in the 2000s at its lowest rate as a percentage of GDP (below 1.5 percent annually) since

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this data began to be compiled at the end of World War II.[4] If this number is adjusted for cost changes, manufacturing fixed capital investment actually declined in the 2000s (down 1.8 percent)—the first decade this has occurred since these measurements began in the 1950s. Investment in the 2000s declined in 15 of 19 industrial sectors measured by Bureau of Economic Analysis (BEA).[5] In contrast, manufacturing investment in the 1990s grew an average of 5.5 percent annually.

Output

While we have assumed from published government statistics that U.S. manufacturing net output as a share of world output has been stable, surpassed last year only by China,[6] we may have been fooling ourselves. A recent report from the Information Technology and Innovation Foundation (ITIF)[7] and other economic evaluations suggest that the official U.S. data on output have been significantly overstated.[8] These data indicate that net output in 16 of 19 manufacturing sectors declined in the 2000s, in many significantly, but they also show that these declines were offset by two sectors, computing and energy.[9] The ITIF and economists make three arguments. First, the number of foreign components used in U.S. manufactured products has risen sharply and they have not been adequately accounted for, thus U.S. output is overstated. Second, although employment in the computer sector declined by 43 percent, a significant amount of computer production moved offshore, and nominal U.S. industry shipments in this sector barely increased, government data included an inflationary output factor for increased computer quality and performance that caused the computing sector's output in the 2000s to be significantly overstated. Third, output in the energy sector was similarly significantly overstated. Adjusting for these factors, the ITIF found that net U.S. manufacturing value actually fell by 11 percent in the 2000s.

Productivity

Since output is a factor in productivity, assumptions about strong growth in manufacturing productivity must be scaled back as well, although manufacturing still significantly exceeds service-sector productivity. The ITIF finds that manufacturing productivity grew by 32 percent between 2000 and 2010, not by the BEA's much higher estimate of 71 percent.[10] As adjusted, the U.S. was 10th in productivity growth among 19 other leading manufacturing nations.

Many thought the U.S. was losing manufacturing jobs because of increased manufacturing productivity. The ITIF finds, however, that productivity gains accounted for only about one-third of the 5.8 million manufacturing jobs lost in the past decade,[11] and a Brookings Institution study contends that the historical pattern of productivity gains leading to job growth remains in effect.[12] This means we have to look elsewhere for reasons why manufacturing lost nearly one-third of its workforce in a decade.

To summarize, U.S. manufacturing employment is down, manufacturing capital investment is down, manufacturing output is down, and manufacturing pro-

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ductivity is lower than previously estimated. Overall, the argument appears strong: the U.S. manufacturing sector is hollowing out.

Why Does Manufacturing Matter?

Despite the foregoing figures, manufacturing remains a major sector of the U.S. economy. It contributes $1.7 trillion to our $15 trillion economy and employs 12 million people in a total employed workforce of some 140 million.[13] Manufacturing workers are paid some 20 percent higher than those in nonmanufacturing jobs.[14] Growth economists tell us that 60 percent or more of historic U.S. economic growth comes from technology and related innovation, and manufacturing dominates the innovation system.[15] Industrial firms employ 64 percent of our scientists and engineers, and this sector performs 70 percent of industrial R&D.[16] Thus our manufacturing strength and the strength of our innovation system are directly linked.

Manufacturing and Trade

Success in a highly competitive world is achieved by nations and regions that produce complex, value-added goods. While world trade in services is growing, world trade in goods is still close to five times that of trade in services.[17] Complex, high-value goods, including capital goods, industrial supplies, transport goods, and medicines, make up over 80 percent of U.S. exports and a significant majority of our imports. The currency of world trade is in such advanced goods, and will remain so indefinitely. And yet, the U.S. was running a $500 billion trade deficit in manufactured goods in pre-recession 2007 and is on track to return to that level soon. As of 2011, that total included a $100 billion deficit in advanced technology products.[18]

It is reasonable to ask whether services will eventually offset our manufacturing decline. After all, if services are 80 percent of our economy, can't we just continue this trend? Well, it's not so easy. The problem is that the modest and gradual growth in our services trade surplus ($160 billion in 2007) is dwarfed by the size and continuing growth of our deficit in goods; thus, the former will not offset the latter any time in the foreseeable future.

Given the net transfer of wealth out of the country that is represented by the trade imbalance, it is hard to avoid the conclusion that the U.S. has been shifting to a consumption-led versus production-led economy. We now arguably have a consumption/production imbalance that carries significant long-term economic consequences.

The "Innovate Here/Produce Here" Assumption

Since World War II, the U.S. economy has been organized around leading the world in technology advances. We developed a comparative advantage over other nations in innovation, and as a result led all but one of the significant innovation waves of the 20th century:[19] aviation, electronics, space, computing, the Internet,

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and biotech.[20] Our operating assumption was that we would innovate and translate those innovations into products, and by innovating here and producing here we would realize the full range of economic gains—from innovation at all stages, from research and development to demonstration and testbeds, to initial market creation, to production at scale, and to the follow-on life cycle of the product. It worked: the U.S. became the richest economy the world had ever seen. For the past half century, the U.S. has been playing out economic growth theory—that is, that the predominant factor in economic growth is technological and related innovation—and demonstrating that it works.

In recent years, however, with the advent of a global economy, the "innovate here/produce here" model no longer holds. In some industrial sectors, firms can now sever R&D and design from production. Codeable IT-based specifications for goods that tie to software-controlled production equipment have enabled this "distributed" manufacturing.[21] While manufacturing once had to be integrated and quite vertical, firms using the distributed model can innovate here and produce there. It appears this distributed model works well for many IT products, as well as for commodity products. Apple is the standard-bearer for this model, as it continues to lead in dramatic IT innovations but sends virtually all its production to Asia.

However, there appear to be many sectors where the distributed model doesn't work and that still require a close connection between research, design, and production. Capital goods, aerospace products, energy equipment, and complex pharmaceuticals are examples of this phenomenon. In these sectors, production and R&D/design are the yin and yang of innovation, with production infrastructure providing constant feedback to the R&D/design infrastructure. Product innovation—incremental advance—is most efficient when it is tied to a close understanding of and connection to the manufacturing process. However, if R&D/design and production are so tightly linked, the innovation stages—R&D and design—may have to follow production off shore, and "produce there/innovate there" may be even more disruptive than "innovate here/produce there." These twin developments bring the economic foundations of our innovation-based economic success into question. What good is a world-leading innovation system if the gains flow elsewhere?

The Innovation Side

If the picture on the production side is problematic, what of the innovation side of the equation? The U.S. has maintained the same national innovation intensity (R&D relative to GDP) it developed in the 1960s, whereas other competitive economies have steadily increased their innovation intensity;[22] in fact, a group of Asian nations has now collectively passed the U.S. in total R&D investment.[23] National Institute of Standards and Technology (NIST) senior economist Gregory Tassey suggests that "input/output" economics theory applies: if you freeze a major input, which the U.S. has been doing increasingly through stagnated R&D intensity, then your growth rate is limited.[24]

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The intensity of federal R&D investment relative to GDP has been in decline for decades in the U.S., falling from nearly 2 percent of GDP in 1965 to 0.7 percent of GDP in 2010; it has been offset by a rise in industry R&D to nearly 2 percent of GDP in that same period.[25] However, the latter is now leveling off. One reason for this leveling off is that U.S. manufacturing firms have dramatically shifted their R&D investment strategies during the last 15 years by taking an increasingly global approach. For example, their off-shore R&D investment has increased at three times the rate of their domestic R&D spending. Tassey argues that U.S. manufacturing firms also have shifted the composition of their R&D portfolios toward shorter term development objectives in an increasingly competitive international marketplace.[26] He argues that the so called "Valley of Death" barriers between R&D and later stage development are actually widening in the U.S., as firms pull back from investment in radical or breakthrough innovation and focus more on shorter term incremental advances.

Nevertheless, even in the face of growing competition, the U.S. retains the world's strongest innovation system, and any advanced manufacturing strategy must seek leverage from this comparative advantage. However, it should be recognized that U.S. R&D has had only a minimal focus on the advanced technologies and processes needed for production leadership; this contrasts sharply with the approach Germany, Japan, Korea, and China have taken to manufacturing R&D. While the major U.S.-based multinational manufacturing firms fund most of the nation's technology development and thus have the capacity to keep up on the innovation front, the majority of the U.S. manufacturing sector belongs to the 300,000 small and midsize firms lacking this capacity. This manufacturing base, which is largely outside our innovation system, represents 86 percent of our manufacturing establishment and employs more than half of our manufacturing workforce.[27]

The Geopolitics of Manufacturing

Since Alexander Hamilton put the financial building blocks in place to transform the U.S. into the world's largest commercial economy, manufacturing has been central to U.S. geopolitical strategy. Barry Lynn of the New America Foundation argues that the U.S. has gone through three evolutionary phases. From the time of Hamilton until 1945, the U.S. pursued national self-dependence in manufacturing and considered it key to national security.[28] Hamilton saw that in a world of dominant and colonizing European powers, the U.S. would retain its independence on the world stage only if it magnified its commercial power, with manufacturing as a critical component. The U.S. pursued Hamilton's basic strategy through World War II and up to the beginning of the Cold War. Faced with a struggle against a Marxist economic model from 1945 until the end of the Cold War in 1991, the U.S. built a series of postwar agreements that entwined the U.S., Europe, and Japan in a system of mutual economic dependence that centered around "America-centric" consumer markets and manufacturing. The geopolitical concept in this period was

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that U.S. national security would be enhanced through an economic embrace of its Cold War allies—essentially a system of mutual economic interdependence intended to build the economic strength to fend off Marxist geopolitical competitors.

The third period began under President Clinton in 1993, with China's entry into the World Trade Organization. The geopolitical concept was to bind the world, not just allies, into an interdependent economic system tied together by open trading, financial integration, and joint manufacturing. The aim was to integrate China into the world economy to ensure peace in a way comparable to Jean Monnet's design for a postwar common market to ensure future European peace. Clinton's perspective in effect embraced a completely laissez faire attitude toward manufacturing. Integrated manufacturing was designed to ensure an integrated world economy, and Hamilton's concept of manufacturing ensuring national security was set aside.

Meanwhile, China pursued a different approach, as it viewed innovation-based growth as the key to its ascendance as a superpower and used neo-mercantilist policies to get there.[29] The Chinese have sought to build an Asian rim of nations whose economies are increasingly dependent on China's economy for their exports and production facilities, and have run a huge trade surplus with the U.S. in manufactured goods to generate the capital to finance its internal growth and offset its trade deficits with the dependent Asian rim economies. Economist Carl Dahlman has portrayed this strategy as a deliberate attempt by the Chinese to hollow out the economies of its competitors with developed economies in order to finance its own geopolitical rise.[30]

In 2004, economist Paul Samuelson asked how the U.S. could be on the losing end economically with a low-cost, low-wage competitor like China, despite the longstanding Ricardo-based economic theory of "comparative advantage" in trade.[31] He noted that if, along with its low-wage advantage, China begins to make gains in production that enhance its productivity it could capture some of the comparative advantage that the U.S. has enjoyed. He added that, in a Ricardo analysis, unemployment from trade never lasts forever, "so it is not that U.S. jobs are ever lost in the long run; it is that the new real wages have been lowered by this vision of dynamic fair trade." In other words, U.S. wages could drop over time to a point where China's production price advantage is offset. The U.S. still has the benefit of lower priced goods, but there are now "new net harmful U.S. terms of trade." Samuelson cites many historical examples of this phenomenon, from the shift of the U.S. textile sector from the Northeast to the Southeast in the early 20th century, to the way Midwestern agriculture surpassed eastern U.S. agriculture in the second half of the 19th century. Samuelson's analysis implicitly suggests that nations like the U.S. that build their comparative advantage on innovation capacity as opposed to resources (the basis for Ricardo's free-trade theory) face a problem: an innovation advantage is not necessarily eternal; it can be overtaken by others as they build their own innovation systems.

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Japan vs. U.S. 1970-1980	China vs. U.S. today
High-cost, high-wage, advanced technology economy—comparable to the U.S.	Low-cost, low-wage, increasingly advanced technology economy
U.S. had entrepreneurial advantage; Japan had industrial policy advantage	China is entrepreneurial and pursuing industrial policy
Rule of law	Limited rule of law
IP protections	Extensive IP theft
Subsidizes currency and buys U.S. debt to limit U.S. opposition	Follows Japan's model: subsidizes currency and is largest holder of U.S. debt; uses foreign currency reserves for sovereign wealth funds to acquire U.S. assets
National security ally for 60 years	Potential national security peer competitor

Table 1. Competitiveness then and now

The U.S. faced an intense competitive challenge in the 1970s and 1980s with Japan and Germany. That was a simpler and more straightforward competition between comparable economies, as opposed to the much more complex competition it faces with emerging nations like China and India. Table 1 illustrates some of the differences in competitive patterns the U.S. has faced, comparing its competition with Japan to that with China.

To summarize, competing with a low-wage, low-cost, increasingly advanced technology economy that lacks compatible systems for the rule of law, IP, and national security, and is following a currency subsidy/debt acquisition strategy, is much more complicated than the competitive pressures the U.S. faced in the 1970s and 1980s. At the same time, due both to inattention and a lack of understanding of its own past success model, the U.S. has departed from a geopolitical strategy that includes the concept of a strategic economic advantage built around production and innovation leadership. The geopolitical issues behind innovation capacity and advanced manufacturing are profound and largely unexamined. Despite the current era of benign neglect, these two interrelated factors largely determined the U.S. national security advantage for a century, and they remain a significant element in understanding the U.S. manufacturing challenge.

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Eroding Advanced IT Sectors

While many economists in the past have preached that the U.S. should cede its lower end manufacturing sectors to emerging economies and offset the losses with the success of the high-end, high-value goods emerging from its leading innovation system,[32] the picture in this advanced technology sector is so unsettling that this standard thesis now looks bankrupt. For example, Gary Pisano and Willy Shih of Harvard Business School have examined the advanced IT sector and found that the most recent edition of the Kindle could not be made in the U.S.: the flex circuit connector, controller, lithium polymer battery, wireless card, and injected molded case are all produced in China, and the electrophoretic display is made in Taiwan. Every brand of U.S. notebook computer (except Apple) and every mobile/handheld device is now designed in Asia. After reviewing the advanced technology sectors created in the U.S. that are now in danger of shifting abroad, Pisano and Shih conclude that major erosion has already occurred in advanced materials, computing and communications, renewable energy technologies and storage, semiconductors and displays, and that the next generation of technology in each area is facing an imminent shift overseas. This is why the U.S. has run a trade deficit in advanced technology goods every year since 2002, and that deficit has now reached $100 billion annually.[33] Given the experience of the past decade, continuing to contend that the U.S. will make up for its manufacturing decline because it will always capture high-end manufacturing can only be considered a game of "let's pretend." Our problems are far deeper than we have acknowledged.

Clayton Christensen of Harvard Business School has argued that, faced with disruptive innovation, established production firms typically relinquish low-margin production and work to retain leadership through incremental ("sustaining") advances in high-margin production. However, these established firms end up ceding those as well, as the disruptive advances that allowed the capture of the low end (and, through lower costs, expanded customer bases) mature and improve to enable the capture of the high end.[34] The argument may prove relevant to U.S. manufacturing strategy; in fact, the U.S. already may be facing disruptive innovations that it has not recognized as such. China, for example, which has now surpassed the U.S. in manufacturing output, apparently is not merely pursuing its low-cost production advantage but is conducting a rapid scale-up of its production tempo and volume through advanced processes that are integrated across firms and tied to cost savings.[35]

Manufacturing as a Multiplier

Manufacturing also matters because it operates as an economic multiplier, creating economic gains that stretch beyond the manufacturing sector. In fact, it is the largest multiplier of all sectors; each manufacturing job is estimated to create between 2.5 and 2.9 jobs in other sectors. High-tech sectors have much higher multipliers; estimates range from 5.2 jobs from a digitized modern factory to 16 in the electronic computing sector.[36] Because gains from production processes can be

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scalable, unlike services, manufacturing also operates as an output multiplier. Every dollar in final sales of manufactured products results in $1.40 in additional output in other sectors.[37] No other economic sector comes close to this level.

Summary: Manufacturing Matters

To summarize, manufacturing matters in a number of ways throughout our economy. Successful nations capture wealth from around the world by conducting trade in complex, high-value goods, not from trade in services. The U.S. is running trade deficits in goods at dangerous levels, and these deficits suggest that the U.S. in effect is running a global wealth transfer machine. These deficits create fiscal imbalances that eventually have to be repaid. The shift U.S. multinational manufacturing firms have made to distributed manufacturing has been accompanied by an approach of "innovate here/produce there." This not only shifts gains from the innovation implementation stage abroad; because of the interrelationship between R&D and design with production in many sectors, it creates the risk that innovation leadership will also shift abroad. The failure of the U.S. to understand the geopolitical realities of leadership in world production potentially jeopardizes the pillar on which we have built our national security advantage for the past 80 years—technology leadership. Our future leadership in both production and innovation in advanced technology sectors, and therefore in the innovation-based growth gains they create, is now in jeopardy in a number of sectors. And, finally, because manufactured goods can scale in an economy, over time our decline in manufacturing may cost our economy a crucial economic multiplier.

Given the critical links between innovation and production, what is to be done?

NINE STEPS TOWARD MANUFACTURING INNOVATION

Growth economics teaches that, as noted above, the dominant causative factor in economic growth is technological and related innovation. This lesson of course applies to the manufacturing sector; in fact, innovation will need to be a primary part of the solution to our manufacturing malaise. We have systematically turned to technological innovation to work our way through past economic dilemmas, and there is every reason to assume that we must approach this one in the same way. If our leading competitors have a significant production wage and cost advantage, we can compete by driving down wages and, correspondingly, our standard of living, or we can compete by leading in technological and process innovations that support major gains in productivity and efficiency and drive down costs to offset our competitors' wage/cost advantages. However, applying our capacity for innovation cannot be the only part of a manufacturing strategy—it must be the heart of it. Alternatively, we could wall ourselves off from the global economy, but we also would be walling ourselves off from potential markets. Moreover, we are already deeply engaged in the global economy, therefore, multiplying productivity and efficiency through an innovation strategy appears to be crucial.

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There are numerous historical examples of nations that have captured a production-based economic advantage through innovation-driven manufacturing technologies and related processes; three are highlighted below. In the 19th century, the U.S. took leadership of the Industrial Revolution from Britain by developing the "American System" of interchangeable machine-made parts—a critical step toward building the mass production capability needed to serve our continent-size market.[38] This was made possible by a 20-year war department technology project directed by John Hall at the Harpers Ferry Arsenal, through which precision machine tools were developed to support the manufacture of interchangeable parts. This dual-use R&D project automated musket production and soon spread throughout the Northeast, which allowed the mass production of simple machines, from clocks to guns to cotton gins.

From the 1960s through the 1980s, Japan's economy was focused heavily on quality manufacturing,[39] which featured new levels of precision in production, "just-in-time" inventory, and made labor a fixed rather than a variable cost in return for workforce flexibility. Japan's efforts were based on core technology advances in computer-driven precision machining and IT systems applied to production, suppliers, and inventory, but also included major process reforms and business models. As a result, Japan gained leadership in the huge international automotive and consumer electronics sectors. Quality manufacturing was the one major innovation wave the U.S. missed in the second half of the 20th century.

A third example concerns semiconductors in the 1980s.[40] While Japan was applying its quality manufacturing strategy and moving to dominate the sector, the U.S. semiconductor industry, allied for five years with DARPA through Sematech, established a collaborative public-private partnership focused on enhancing production efficiency and productivity in its supplier sector. This effort played a key role in restoring U.S. technology leadership in the semiconductor sector.

Each of these examples contained three elements: (1) core *technology* advances, which were implemented through (2) new *process* advances and realized significant industry gains through the (3) new *business models* they supported. Put another way, a technology advance is worth little if it can't be incorporated into new production processes, and it will never be implemented unless a new business model is developed to realize its potential economic gains. All three stages are necessary and intertwined.

In addition, as the U.S. considers what steps to take to revitalize the manufacturing sector, it is important to emphasize that this sector is divided into industry sectors—for example, pharmaceuticals are different from aerospace, which is different from chemicals. There are major differences within the industry sectors as well. We will concentrate here on three groups.

Large multinationals (MNCs). They are international, will locate in low-cost production centers, and need to be in emerging world markets. They have substantial access to capital and financing and conduct applied research and development.

Small and midsize enterprises (SMEs). There are 300,000 SMEs in the U.S. man-

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ufacturing sector; they are suppliers and component makers for the MNCs. They typically are thinly capitalized, must be risk averse, and conduct little or no R&D.

Start-up and entrepreneurial firms. They exist particularly in expanding sectors like IT, biotech, and renewable energy; they appear to be increasingly offshoring production because it's usually not a firm core competency, and they have limited access to production financing.

Each of the issues discussed below must be translated back to and seen through the lens of these groups of firms concerned with manufacturing.

Although most manufacturing industry trade associations press for macroeconomic strategies around trade, tax, currency valuation, and regulatory policies, the emphasis here is on an innovation-intensive strategy. This is in part a lesson of the Great Recession, which continues to affect our economy. We have attempted to counter the recession through a standard Keynesian response—a $780 billion stimulus program that operated at a macro-economic level. Yet the very slow recovery from the Great Recession suggests that it was not a standard business cycle recession that would respond to a broad macro-economic stimulus; it appears instead to be a structural recession rooted in shifts in particular segments of our economy.[41] In contrast to the effect on a business-sector recession, a macroeconomic stimulus will have only a limited effect on a structural recession—it is more a stabilization tool than a recovery and growth tool. The data discussed above on the extent of the U.S. manufacturing sector's decline suggest that structural issues in the U.S. economy's recession were rooted not merely in the related housing and financial sectors but in the manufacturing sector as well. A structural decline is the likely explanation for the decline in manufacturing employment, capital investment and output, and the lower than assumed productivity increases—all of which are developments that cannot be explained as a business cycle response. If there are structural problems in the manufacturing sector, a macroeconomic response alone is not going to work. Instead, a deeper structural understanding of the manufacturing sector is required and an innovation-oriented response must also be considered, since advances in technology and related processes are the source of the efficiency and productivity gains needed, as discussed above, to alter sectoral performance.[42] In other words, manufacturing is at the heart of a recession recovery, and macro measures alone won't be enough—innovation system solutions are needed because we have structural problems.

Below are nine steps that could be the foundation for a manufacturing innovation strategy. The emphasis is on identifying possible approaches, not on final answers. But these are steps that can be taken toward reinventing manufacturing in the U.S.

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Step #1: What technology advances could yield new manufacturing productivity paradigms?

Manufacturing is already deep into a technology transformation. In the past quarter century, manufacturing has moved from labor-intensive mechanical processes to information-intensive processes. Unlike education and government, two sectors that have resisted the Information Technology (IT) revolution, manufacturing embraced it early on, which led to significant gains in productivity. This IT-intensive trend will continue and accelerate as new IT advances come to bear, including the use of advanced computer simulation and modeling in product design, IT systems embedded in products at every stage of the production system and product lifecycle, continued IT-derived efficiency gains in supply-chain management and the distribution system, and more flexible manufacturing that allows unique, customer-driven designs.[43]

The way U.S. manufacturing could compete with low-cost, low-wage economies that have increasingly advanced technology is through, as noted, major gains in productivity that more than offset their cost advantages. Therefore, technology innovation and related processes must be at the core of any strategy. That said, are there new manufacturing technology paradigms that the U.S., taking advantage of its remaining innovation leadership, could bring into its manufacturing sectors? Could we undertake a technology revolution comparable to the one Japan introduced four decades ago around quality manufacturing? The following areas of advance arguably offer such transformative possibilities:

"Network centric." A continuation and acceleration of existing IT-intensive manufacturing that includes a mix of IT advances, Radio Frequency Identification (RFID), and sensors in every stage and element of the production process—from resource through production through product lifecycle—with new decisionmaking tools from "big data" analytics, along with advanced robotics and supercomputing with accompanying simulation and modeling. In addition, software is now a major component in complex products. The high cost and complexity of software currently inhibits efficient production, thus integrating software development with design at the outset, along with creating new systems for hardware/software integration, also appears key.

Advanced materials. Create a "materials genome"—the ability, using supercomputing, to design all possible materials with designer features and to fit new materials precisely to product needs for strength, flexibility, weight, and production cost. In addition, evolve new biomaterials from synthetic biology, explore biofabrication, and make everything lightweight.

Nanomanufacturing. Fabrication at the nano-scale and embed nano-features into products to raise efficiency and performance.

Mass customization. Production of one item or small lots at the cost of mass production; for example, through 3D printing/additive manufacturing.

Distribution efficiency. Squeezing even 10 percent out of the cost of product

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distribution can shift decisions about whether to produce at home or abroad; further IT advances that yield distribution efficiencies, including in the supply chain, could yield this.

Energy efficiency. Excess energy is "waste"—a largely nonrecoverable production cost—and U.S. manufacturing has long been overly energy intensive. Conservation and energy efficiency technologies and processes could significantly drive down production costs.

This is certainly not an exhaustive list; it is only illustrative.[44] The selection process for focus areas should be dynamic and ongoing and take advantage of emerging technology options. Defense Advanced Research Projects Agency (DARPA) administrators Regina Dugan and Ken Gabriel have argued that "the 19th century was about manipulating energy, the 20th century was about manipulating information, and the 21st century will be about manipulating matter."[45] DARPA is making major investments in advanced manufacturing R&D, which it views as vital to "accounting for time"—that is, sharply cutting the time between product conception, prototype, and production so that the Department of Defense (DOD) can move from its slow and expensive system of "buy then make" to "make then buy." If DARPA's efforts to slash time to production are successful for DOD, its approach to saving time could be a sea change for manufacturing in general.

The obvious question is, won't low-cost, low-wage competitors simply implement the same efficiency approaches? Not necessarily. As Japan demonstrated when it developed its quality manufacturing paradigm, there is a first-mover advantage that can assure leadership for a significant period. Offsetting a low-cost, low-wage competitive advantage with gains in productivity levels an essential playing field, and it won't be simple for a labor intensive emerging economy to shift from its initial competitive cost/wage advantage without significant disruption.

Won't this require a major new R&D programmatic effort? Interestingly, four leading R&D agencies, DOD, the National Science Foundation (NSF), the Department of Energy (DOE), and the National Institute of Standards and Technology (NIST), are already undertaking significant R&D programs directly, not just indirectly, in the advanced manufacturing space. A 2010 survey drawn from agency data and program summaries indicates that these four agencies were investing approximately $700 million a year;[46] the level increased to approximately $800 million annually by 2012. This may not be large enough, but it is a reasonable start, and leveraging for manufacturing advances is possible from other research sectors, such as artificial intelligence and advanced materials. What is missing is closer industry-university-regional collaboration and cross-agency coordination, which must be coupled with a technology strategy and eventually a public-private roadmapping exercise. The recent report of the Advanced Manufacturing Partnership has called for exactly these steps.[47] Therefore, a foundational R&D investment is in place and ready to be called on but should be joined with interagency and private-sector collaboration.

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Can technology innovation translate into dramatic manufacturing productivity gains and efficiencies? Obviously, there are numerous historical examples of this, such as the way interchangeable machine-made parts led to mass production. More recently, Japan's quality manufacturing paradigm and IT-intensive manufacturing had comparable effects. What's a current example? Tonio Buonassisi, Doug Powell, and their MIT colleagues have closely examined the cost structure of crystalline solar photovoltaics (PV);[48] if this technology is to be competitive with other technologies that produce electricity for residential and commercial uses, it must continue to dramatically cut production costs. Major international R&D efforts are under way to do this on a pathway that resembles what Moore's Law did for semiconductor efficiency and performance. DOE calls its program Sun Shot, implicitly comparing it to the Moon Shot of the 1960s. If achieved, this could be an economic sector worth trillions of dollars. Innovations that are now being explored and are in range ("line of sight" innovations, such as high-efficiency cell architecture, improved silicon utilization, high-quality thin kerf-less wafering approaches, and production and module improvements) will move this technology far along on that curve. Breakthrough innovations now being researched (including tandem cell architectures, band structure engineering, and advanced light trapping) would advance it well past the goal line. Buonassisi and Powell indicate that if the U.S. continues to push these innovation efficiencies for the rest of this decade, they can erase the production cost advantages China currently enjoys in solar PVs and enable the U.S. to be fully competitive in this sector, even if the technology advances are simultaneously transferred to China.[49]

In conclusion, if the U.S. wants to compete with low-cost, low-wage, increasingly advanced technology competitors in production, it appears to be critical that it strategically and systematically invests in and applies its comparative advantage in technology innovation to create a series of new manufacturing technology paradigms comparable to past paradigms constructed around interchangeable parts and quality.

Step #2: Pick new manufacturing technology paradigms that apply across a range of manufacturing sectors.

Manufacturing is sectoral, but there has been increasing overlap of the sectors producing complex, high-value goods. For example, most cars still have internal combustion engines, but they also need from 30 to 60 processors and ever more intricate software systems to run them. An airplane is a complex system, combining aeronautical design, turbine engines, electronics, advanced materials, software, and information technology. Improvements in one sector therefore translate to other sectors producing complex goods.

Generally, however, it would be important to create as much synergy as possible when pursuing technology paradigms. In other words, in selecting which technology paradigms to pursue, those with relevance to a series of manufacturing sectors should be given priority. This strategic selection of innovation emphases, then,

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Sector and *Manufacturing Paradigm*	Bio/ Pharma	Aero-space	IT/ Electronics	Heavy Equip.	Digital Search, Network	New Energy	Transport
Network-centric	x	x	x	x	x	x	x
Advanced materials	x	x	x	x		x	x
Nano manufacturing	x	x	x	x	x	x	x
Mass customization	x	x	x	x	x	x	x
Distribution efficiency	x	x	x	x		x	x
Energy efficiency	x	x	x	x	x	x	x

Table 2. Matrix: Industry sectors/manufacturing paradigms

should be focused on transferability across sectors. We should run a matrix that compares technology options against the sectors they apply to, selecting for focus technologies with payoff across sectors. The technologies listed in Step #1 appear to translate well into a range of industrial sectors, as suggested in Table 2.

Additional variables that fit in multiple sectors and are worthy of consideration include the maturity of the technology embedded in the paradigm and the time it may take to translate it into implementation, the readiness of relevant sectors to undertake that translation, market demand, U.S. national security needs, and the ability of an enhanced sector to translate into U.S. economic benefits.[50]

Step #3: Technology alone is not enough—there is a need to look at all three: advanced technology, process, and business model.

A new generation of advanced manufacturing technologies alone will not be transformative. There must be a realization that developing technologies without new process and business models to foster implementation is unworkable. As discussed in the introduction to this section, although new advanced manufacturing technology paradigms will be a first building block, there must also be new process models to adapt them to the production system and realize their efficiencies. New business models will be needed as well, because the technology paradigm has to work economically, with significant and demonstrable economic gains flowing to the firms that implement it.[51] These new process and business models must be built into a technology R&D effort right along with the technology development. In sum, technology is not all there is to a manufacturing technology strategy.

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Step #4: It's no longer manufacturing or services; the integrated model will prevail.

The 21st-century firm increasingly fuses services, production, supply-chain management, and innovation. Many of these capabilities are knowledge intangibles rather than fixed assets, and will require learning to tie advanced manufacturing (including new technologies, equipment, and processes) with IT-informed service models.

IBM was probably the first large firm to create the modern fused model. When CEO Lew Gerstner arrived at IBM to pull it out of a financial crisis, the prevailing approach at the time was to carve up firms into smaller focused units and sell them off.[52] Gerstner decided to do the opposite, electing a unified firm with great breadth, keeping its historically strong R&D with a range of IT hardware offerings, and tying both to a new services effort, which offered customers not only technology but what IBM called "solutions" to IT challenges. The result was one of the great business turnaround stories in the late 20th century. IBM's fused model subsequently was emulated throughout the IT sector.

It should be noted that the fused production/services model doesn't have to be vertical and integrated into single firms; it can be horizontal and include links between firms that have a range of services and production capabilities, thereby leveraging specialized capabilities from particular partner companies. Moreover, the model is not only about business organization; there are increasing numbers of merged products with both hardware and services features. Apple's iPod is emblematic of this approach, as it combined a capable MP3 player with a new highly efficient and low-cost system for delivering music, and now other applications. When the "business model" stage of advanced production is being planned, the fused services/production approach must be considered.

Step #5: Better look over our shoulder . . .

The U.S. did not lead the last manufacturing revolution. Japan took the lead around a quality model,[53] and U.S. manufacturing had to play catch-up for a decade. Thus there is no reason to assume the U.S. will necessarily lead the next wave, with the mix of advanced manufacturing technologies cited in Step #1. Germany and Japan are large, established manufacturing powers that run major surpluses in complex, high-value goods. Korea, Singapore, and Taiwan operate on a smaller scale but they are leading in key sectors and expanding their manufacturing employment. China, India, and Brazil are emerging large manufacturing powers that are following a low-cost, low-wage, increasingly advanced technology approach. All are adopting new competitive models; the U.S. must understand its competitors' approaches if its own are to be successful. We have much to learn from these competitors.[54]

There is a substantial argument that the advanced manufacturing technologies cited in Step #1 will all emerge and become pervasive over the next decade and a half. Just as survivor U.S. firms had to launch "lean" manufacturing to compete

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with Japan's quality manufacturing model of the 1970s and 1980s, today's firms will either implement these advanced technology paradigms or fail. How these advances will reach the core of U.S. manufacturing—the 300,000 SMEs that lack integrated R&D—is particularly problematic.

Step #6: Build the workforce.

Advanced manufacturing will require an ever more skilled workforce, yet a gap in manufacturing skills appears to be developing. A 2011 survey conducted by the Manufacturing Institute and Deloitte indicates that 82 percent of responding manufacturing firms had experienced moderate to serious problems with the availability of skilled manufacturing candidates; 74 percent of manufacturers reported that this skills gap had affected their ability to expand operations.[55] The respondents reported that, despite the high unemployment rate, 5 percent of manufacturing jobs were going unfilled because of problems with lack of skills. The survey did not study whether significantly higher compensation could alter this problem, but it is nonetheless indicative of a problem manufacturers felt to be widespread.

A root cause of the problem may be manufacturing's image. Despite the fact that manufacturing jobs are better paying than jobs in other sectors, a survey of engineering and science undergraduates found limited interest in manufacturing as a career.[56] The history of manufacturing plant closings and job off-shoring may be contributing to this perception.[57] Advanced manufacturing and production innovation that call for high skills and technology challenges may help alter the image problem, but skills training must still be improved.

The nation's 1,500 community colleges have become the major providers of technicians, and this role can be made more efficient and expanded. Programs are afoot to build stronger ties between industry and community colleges by providing standardized skills training curricula at community colleges that would lead to skills certifications that have acceptance throughout industry.[58] At the professional level, undergraduate engineering programs offer only limited manufacturing content. Yet unless engineers become fluent with advanced manufacturing technologies, these technologies simply won't translate to industry and into production processes. Nanofabrication is being performed at research benches, but until it reaches the factory floor it cannot be transformative; skilled engineers are traditionally the process translators. New technical master's degree programs in manufacturing could be helpful; it would be more useful for universities to develop online curricula around advanced manufacturing technologies and processes as a way to educate both new and current engineers and technicians. The training and education solutions are legion, but without advances in the workforce, advanced manufacturing paradigms cannot be implemented at scale.

One major competitive advantage for the U.S. historically is that it kept making significant improvements in the education of its workforce at a rate that exceeded its industries constantly growing demands for ever-higher technological skills.[59] The U.S. invented mass higher education through the 1862 Morrill Act

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land-grant public university system and multiplied college graduation rates following World War II through the GI Bill—perhaps the two most important pieces of U.S. social legislation ever passed. The fact that the U.S. built a large base of college graduates long before any other country gave it a competitive technology advantage throughout almost the entire 20th century. The U.S., therefore, was the first country to implement a system in which talent became a truly dynamic innovation factor; its talent base sized its innovation capacity, not the other way around.[60] However, U.S. college graduation rates have stagnated in recent decades, while rates in other nations have been sharply increasing, thus eroding this historic U.S. competitive advantage. Degrees in science, technology, engineering, and mathematics (STEM) in particular have stagnated, and 60 percent of those intending to major in STEM fields in U.S. colleges drop out of those fields.[61] Since the manufacturing sector is a dominant employer of the U.S. innovation workforce, altering this STEM dropout rate by even 10 percent could significantly expand the talent base required for future advanced manufacturing.

Step #7: Innovation organization—correcting the problem of the pipeline and the seams.

Growth economics has developed two core direct innovation factors: R&D that supports technological and related innovation, and the talent base behind it.[62] However, these alone are not enough for implementing and scaling innovation in society. A dynamic, "connected" system that links these factors and the institutional innovation actors that perform them, tying them to implementation stages in industry, is also key.[63]

Dan Breznitz of Georgia Tech and Peter Cowhey of UC San Diego have argued that the U.S. needs to link the two innovation systems it maintains more effectively.[64] The first, the novel and breakthrough product/technology innovation system, includes university research supported by R&D agencies. It is often known as the "pipeline" system and uses "technology push" to implement its advances. The second, the process and incremental innovation system, emphasizes engineering enhancements for products and technologies, including the way they are produced, distributed, and serviced; it is dominated by industry.[65] Both are vital, yet our current technology policy model pays great attention to the former and little to the latter; furthermore, the first system rarely comes to assist the second. Manufacturing historically has fallen into the second category, as it is considered to be dominated by engineering/process and industry, although, as has been demonstrated repeatedly over the decades, it can be novel and innovative as well. It has never been the focus of a major federal R&D effort, which is one reason the U.S. continues to innovate technologies while the product evolution occurs abroad. Suppose we worked to unify our systems and brought the remarkable innovative talent to support the second as well as the first? This innovation organization reform is an important part of what we must accomplish if we are to implement new manufacturing technology paradigms.

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So what would this look like? As noted above, the four leading U.S. R&D agencies active in advanced manufacturing research are already investing annually over $700 million in R&D that bears directly on this field.[66] If indirect areas are included, the number is significantly higher. For example, overall advances in materials, advanced computer simulation and modeling, robotics, and nanotechnology have important ramifications if translated into manufacturing. The lead agencies—DOD, DOE, NSF, and NIST—have already begun to collaborate and have a cooperative strategy.[67] Close collaboration across agencies with true interagency R&D efforts, including shared funding and programs, as opposed to exchanges of data and ideas across agency walls, has not been achieved in the highly decentralized U.S. R&D model—not even the noted attempts at cross-agency work in the National Nanotechnology and High Performance Computing initiatives. Moreover, strong ties with industry work will be required if the two innovation systems identified above, novel/breakthrough and incremental/engineering, are to be connected.[68] The lessons of a unified R&D effort that includes R&D, process, and business models, as described in Step #3, must be applied. This will be critical if the relatively modest direct manufacturing R&D efforts, as well as the far larger indirect efforts, are to launch new technology paradigms on the factory floor.

The resources of the DOD will also be required. While other federal R&D agencies operate at the research stage under the Vannevar Bush pipeline model, DOD operates at all stages of the innovation system: it performs the research, the development, the prototype, the demonstration, the testbed, and often creates the initial market for new technologies through its procurement system. Because it can operate as a connected innovation system, it is not an accident that nearly all the major innovation waves of the second half of the 20th century have relied on DOD, from aviation and space to computing and the Internet.[69] That systemic role will be needed for advanced manufacturing, where DOD's contracting role makes it a major actor. It also has a huge stake in maintaining U.S. technological leadership, which is the central element of U.S. leadership in world security.[70] Gains in efficiency and productivity will be key to DOD's ability to control its procurement costs and, because of the relationship between R&D/design and production, to its future technological edge. Because of the inherent strength of its connected innovation system, DOD will need to be a central agency partner in any advanced manufacturing strategy.[71]

The technology push from our federally driven R&D pipeline innovation system will be needed for the transformation of manufacturing, as it has been in many innovation fields (aviation, space, nuclear power, computing, and the Internet). The seams between agencies in this field need to be erased, otherwise the needed research scale over a range of technologies cannot be assembled. Our highly decentralized system of diverse federal mission-driven R&D agencies has many advantages, but where cross-cutting innovation collaboration is required, decentralization can be a barrier to innovation. In this field, we need shifts in innovation organization to get across the agency seams.[72]

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Step #8: Build regional infrastructure.

Manufacturing in the U.S. is not a national system but regional; it is based in industry sectors and connected clusters spread throughout the country. Any advanced manufacturing effort must be organized around that regional reality. It can't simply be an R&D program run at the national level, it must connect to the regions where manufacturing is organized and advances must be implemented.

In addition, while R&D conducted by the government and universities can take a technology from basic research through proof of concept and early stage development, it usually does not advance to the later stages of technology demonstration and system/subsystem development phases. There are seams between these innovation stages, which are usually performed by different innovation system institutional actors. All the seams between the stages and the institutions must be crossed.[73] While large firms may have the capability to undertake those later stages, the 300,000 small and midsize manufacturers that form the bulk of the U.S. manufacturing sector are not organized or funded to do so. Thus, the federal R&D system has a problem connecting with regions, and in transitioning technology from development to later stages, particularly for smaller firms. This mass of smaller firms must be risk averse to survive; it lacks the resources to undertake R&D, testing, and evaluation, and it lacks the capital to implement new technologies. Unless the new advanced manufacturing paradigms are fully tested, costed out, efficiencies demonstrated, and reliability proven, they simply will not be adopted on actual factory floors by smaller manufacturers.

We adapt to the reality of this regional scale-up, but what are its implications in more concrete terms? We need a new kind of regional infrastructure that ties regional manufacturing firms, small and large, with the results of research and into testbeds where new manufacturing technologies can be proven. The Advanced Manufacturing Partnership has proposed a network of these "Manufacturing Innovation Institutes" as places to select advanced technologies relevant to regional firms, where teams of industrial and academic experts from a range of fields can work on these intermediate stages.[74] Area firms would participate and bring in their workforces to train for implementation. They could share costs between regional industry, state[75] and local governments, and the federal government. The focus would be on translating technologies into manufacturing applications, and giving attention to new industrial processes and the information needed to organize new business models around them.

Step #9: Financing advanced manufacturing implementation.

Large U.S. firms have used off-shoring production to low-wage, low-cost nations to avoid the cost and risks of undertaking innovation in production.[76] Thus, not only is advanced manufacturing technology innovation beyond the reach of small and midsized manufacturers, it has been avoided by larger manufacturers who can send production off shore to lower costs, although to less efficient producer nations. This means that the loss of production capacity throughout the U.S. man-

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ufacturing system is leading to a reduction in the innovation capacity of U.S. firms generally, particularly in manufacturing process technologies. Erica Fuchs of Carnegie Mellon, who has explored this development, cites the lack of financing for implementing production advances as a root cause of this problem.[77] If financing were available, many firms would opt for advanced production technology options; instead, technologically challenging capital investment options in manufacturing in the U.S. are being foreclosed by the lack of capital.

The U.S. developed a new capital financing system for technology advances during the IT revolution, an entrepreneurial system supported by venture and angel capital. It was a brilliant new system for technology advance, and countries around the world have been racing to try to replicate its success. However, there is a problem with adapting it to other sectors. Venture capitalists (VCs) fund startups on a yardstick that is no longer than five to seven years, which fits well with the IT sector. VCs fund firms with technologies no more than two or three years away from commercial production, then recoup their investment through an IPO no more than three or four years after that. Although the five- to seven-year yardstick works in the IT sector, it does not work for many other sectors, including manufacturing, where the scale-up process may take 10 years or more. U.S. innovation policy has long been focused on the Valley of Death between research and late-stage development. Fields like manufacturing first require complex technology development, and then they face difficult and expensive technology integration and scaling challenges. So, in addition to the traditional Valley of Death problem, they face a "Mountain of Death" problem in moving from the technology development stage to implementation at scale. The five- to seven-year yardstick of our VC/angel investment system does not work for the 10-plus-year yardstick of manufacturing and comparable sectors. Since our commercial lending system is increasingly organized around financial instruments rather than investment,[78] there is little refuge in that sector either.

What are the "work-arounds" for this Mountain of Death? First, there may be new approaches on the front end of the innovation system—the R&D stage through demonstration. U.S. R&D agencies have traditionally focused on the research stage and considered the implementation stage "NMP"—not my problem. In the energy field, which also faces the Mountain of Death/10-plus-year yardstick problem, the new Advanced Research Projects Agency-Energy has rejected the NMP tradition. It consciously selects energy technology options that can fit into the cost range required by markets, makes driving down production costs part of its R&D process, and ties its technology development teams to commercialization teams that work in parallel to bring the technologies toward commercialization.[79] All three steps on the front of the innovation system for manufacturing must be considered.

On the back end of the innovation system, aside from a new look at VC and traditional commercial lending, we may need to consider new financial instruments. Some people are looking at new tools that would allow much larger investor pools to be assembled around broad portfolios of new technology firms, with lim-

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ited dollar exposure for individual investors to control risk;[80] the concept is known as crowdfunding.[81] Meanwhile, the testbed step discussed in Step #8 remains key; if the efficiency, cost savings, and productivity of new advanced manufacturing technologies can be fully demonstrated, especially to small and midsized manufacturers, then lending may follow because higher investment certainty is provided.

These work arounds are not only important to existing firms, small or large, they also are vital to startups. It appears that startups are increasingly advised by their VC financers to send the risk and cost of production to contract manufacturers abroad.[82] This has major implications, as noted above, for the future of U.S. manufacturing: we may be losing production capability for the next generation of goods, with corresponding damage to the tie between innovation and production, which would further affect innovation capacity.

CONCLUSION: UNDERSTANDING THE HOURGLASS

U.S. manufacturing currently employs some 12 million workers—a significant number, but less than 10 percent of the total U.S. workforce and much lower than it once was. We look at this manufacturing workforce as those engaged in the actual production—at the moment of production—missing a wide range of inputs and outputs. However, should we limit our view of manufacturing to the production moment, which provides only a partial perspective on the role of this sector?

The manufacturing sector is perhaps best viewed as an hourglass. (See figure 1 on opposite page). The center, the narrow segment of the hourglass, represents actual product production. Manufacturing employment, however, must be looked at in terms of more than just the production moment. Production involves a much larger input employment base, which includes those working in resources, those employed by a wide range of suppliers and component makers, and the innovation workforce—the 64 percent of U.S. scientists and engineers employed by the industrial production sector. Another host of jobs flows out of production, including those in the distribution system, retail and sales, and for the lifecycle of the product. The employment base at the top and bottom of the hourglass is in fact far bigger than those engaged in the actual production moment.

Lengthy and complex value chains involved in the production of the goods are arranged throughout the hourglass, from resources to suppliers and components to innovation, through production, to distribution, retail, and lifecycle—a great array of skills and firms, and largely what we would count as services. Nevertheless, they are tied to manufacturing. If we removed the production element, the center of the hourglass, what would happen to those value chains of connected companies? They would face significant disruption. While the lower base of the hourglass, the output end, might be partially restored if a foreign good were substituted for a domestic good, such as a Hyundai for a Chevy, the particular firms involved would be disrupted. The upper part of the hourglass, however, the input end, with its firms and their employees, would not be restored.

When these complex value chains are disrupted, it is very difficult to put them

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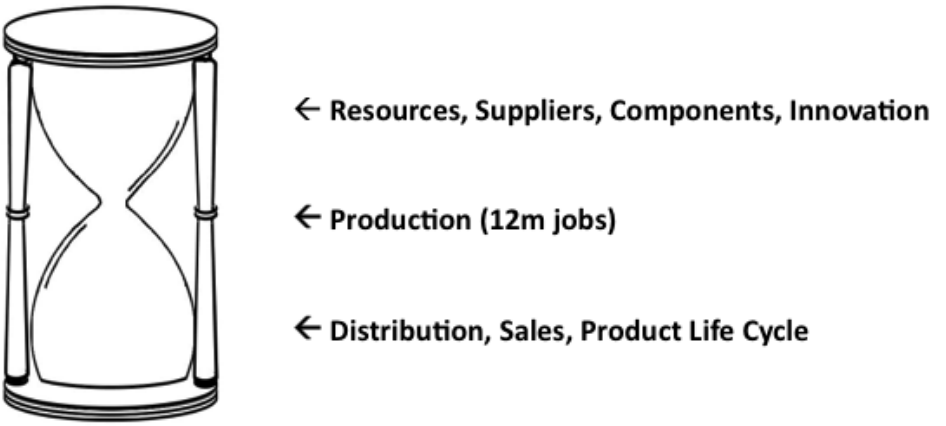


Figure 1. The manufacturing industry viewed as an hourglass

back together. That is why, historically, once the U.S. loses an economic sector, it is so hard to resurrect—it simply won't come back. However, we don't collect such data on our industrial sector; the closest we have is the job multiplier data cited above, which doesn't tell the full story. Understanding manufacturing in terms of the hourglass and the value chains within it may partially explain the economy's current predicament over job loss, job creation, and declining median income.

The U.S. must develop an integrated strategy if it is to reinvent its production capability. It should include the nine steps listed below:

- Developing advanced technologies that could lead to new manufacturing paradigms
- Selecting manufacturing paradigms that apply across a range of sectors
- Integrating technology development with efforts to develop new processes and business models
- In doing this, encompassing the new combined services/production model
- Tracking where world production competitors are moving
- Building at all levels a new advanced manufacturing workforce
- Applying an organizational model that works across the seams between the R&D agencies
- Creating new regional public-private infrastructure for testbedding and implementation
- Tackling the financing problem for advanced manufacturing

These are not the only measures required. There are critical macro-economic policy problems around taxes, trade, currency valuation, and regulatory policy that must be addressed as well. Nevertheless, growth economics teaches that technological innovation and related process are central to growth, and it hard to envision a

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workable manufacturing strategy that does not include a central focus on innovation. Macro-economic efforts without a corresponding innovation-oriented strategy will not address the structural economic problems the U.S. manufacturing sector faces.

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 make geometric increases possible. Production is in fact the major enabler of increasing returns rather than decreasing returns in an economy;[83] it is inherently the largest societal wealth creator we know.[84] Because of its scaling effect, modern societies need to be careful to retain a focus on manufacturing and not settle for services with slower scaling. In this century, one sector will be deeply tied to the other, with corresponding interdependent strength. The United States needs both.

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