ENSURING AMERICAN MANUFACTURING LEADERSHIP THROUGH NEXT-GENERATION SUPPLY CHAINS

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EXECUTIVE SUMMARY

Since 2001, the year China joined the World Trade Organization, the United States has lost nearly one-third of its manufacturing jobs and the workers employed in manufacturing has declined to 12 million.[1] Since then, China has become the world's factory, now accounting for nearly half of global manufacturing output. Dense networks of diverse suppliers in virtually every industry, combined with extensive government support, make China the world leader in manufacturing value-added. The capability has become so great that many American startups, and even established companies, often assume that China is where manufacturing is done. Meanwhile, technically advanced, high-wage nations such as Germany and Japan have maintained strong manufacturing sectors.[2]

[1] The number of U.S. manufacturing jobs peaked in 1979 at 19.5 million; in March 2017, manufacturing employment was 12.4 million, a decline of more than 36 percent.
[2] According to the World Bank, manufacturing value added as a percentage of GDP in 2015 was 23% in Germany, 18% in Japan, 12% in the United States, and more than 30% in China. See http://data.worldbank.org/indicator/NV.IND.MANF.ZS.

Suppliers now account for 50-70 percent of a typical manufacturer's final production value. **How U.S. manufacturers manage their supply chains has been the key to offshoring production and will be the key to rebuilding a robust manufacturing sector.** Traditional purchasing practices, in which buying decisions are based on the lowest unit cost with acceptable quality and delivery, drove much of the shift to Asian suppliers. As Asian capabilities progressed, a more diverse range of products were imported from Asia, mostly China. Some U.S. suppliers responded by building production facilities or contracting production in China, while others, unable to compete, failed. The number of U.S. manufacturing establishments, 292,825 in 2015, has declined by more than 41,000 since 2005.[3]

A growing number of U.S. manufacturers, however, have recognized that this model of supply chain management does not provide a sustainable competitive advantage. If their products are made in the same factories as those of their competitors, product differentiation too often has become superficial. Regaining a competitive edge requires a different approach to managing suppliers, one in which the total supply chain is managed to maximize value. Suppliers are treated as partners, contributing design and engineering ideas. Manufacturing capacity, production planning, and delivery schedules are closely coordinated. Rather than a strict focus on low unit price, broader considerations of cost, flexibility, consistency, and risk minimization—collectively known as Total Cost of Ownership—drives purchasing decisions, at least for high-value parts and components. Many specific tools and techniques for building strong supplier partnerships have been created, and could be more widely used with appropriate training and information sharing.

In some industries, collaboration is aided by new technologies and management practices.

- Enterprise Resource Planning/Supply Chain Management (ERP/SCM) systems include suppliers, and have become more accessible to smaller firms as cloud-based software-as-a-service (SaaS).
- Sensors and advanced control systems have started to allow for predictive analytics that minimize factory downtime.
- Three-dimensional (3D) modeling and simulation is allowing faster, more precise design, rapid prototyping, and direct transfer to computer-controlled production equipment; and
- New production processes such as 3D printing are reducing part counts and enabling more specialized, precise production.

Suppliers with innovative ideas are finding eager customers that expect them to contribute to continuous improvement. Next generation supply chains will apply these and other technologies resulting in U.S. manufacturing that is more competitive, flexible, and responsive to diverse customer demand.

The national challenge is moving from the current situation, in which foreign suppliers are too frequently the default choice and many domestic suppliers have weak capabilities or no longer exist, to an innovative future supported by vibrant supply chains in which U.S. manufacturers compete globally based on innovation and unique domestic production capabilities. Private companies, large and small, will need to reassess their approaches to supply chain management using the tools and best

[3] U.S. Census Bureau, County Business Patterns 2005-2015, at https://factfinder.census.gov/faces/ tableservices/jsf/pages/productview.xhtml?pid=BP_2015_00A1&prodType=table.

practices that have proven to be successful and that lay the groundwork for full implementation of next generation supply chains. However, business cannot meet this challenge on their own. Government at all levels, as well as colleges and universities, have important contributions to make.

NEXT STEPS

Achieving the next generation supply chain, with all the promise of flexible, customized, responsive production, is a complex proposition, requiring contributions from all the players in the manufacturing ecosystem. Obviously, business will take the lead, implementing tools and systems that provide competitive advantage, but government and educational institutions have important contributions to make, both as suppliers in their own right and as facilitators, collaborators, researchers, and suppliers of trained and educated workers. In fact, all of these sectors play integral roles in the manufacturing ecosystem. For the United States to maintain its leadership in innovation, the collective strengths of the full ecosystem must be leveraged.

COMPANIES

Original equipment manufacturers (OEMs) should

- create and implement a supply chain strategic plan that minimizes the adverse effects of organizational silos, maximizes opportunities for shared value creation, and assesses risk exposure and mitigation.
- consider the impacts of sourcing decisions on quality and innovation, based on Total Cost of Ownership, not just on price per unit purchased.
- offer suppliers assurance that they will receive a fair return on investments in new technologies and in upgrading their capabilities.
- promote information-sharing and be willing to make changes in response to supplier suggestions.

Suppliers should take advantage of opportunities to enhance their capabilities as valued partners in supply chains. Assistance from the local Manufacturing Extension Partnership (MEP) center or other provider can help with training and implementation of capability upgrades.

Firms of all sizes should accelerate progress implementing lean production methodologies and other proven management practices to facilitate implementation of supply chain management information systems, data analytics, and other digital manufacturing technologies.

GOVERNMENT

The numerous federal programs (58 programs across 11 agencies) that support manufacturers in some way,[4] especially those in the Department of Defense (DoD), Department of Energy (DoE), and the National Institute for Standards and Technology (NIST) that provide technical assistance, should coordinate their activities based on clear strategic objectives, performance goals, and metrics to maximize return on investment to taxpayers.

MEP should be encouraged to expand beyond its historic focus on serving small manufacturers one at time, to promoting healthy supply chains and regional ecosystems.

The Manufacturing USA institutes should create explicit strategies for developing domestic supply chains in their respective technology focus areas to ensure that technologies matured at the institutes are manufactured and applied in the United States.

[4] U.S. Government Accountability Office, "U.S. Manufacturing: Federal Programs Reported Providing Support and Addressing Trends," March 2017, at https://www.gao.gov/products/GAO-17-240.

MEP and the Manufacturing USA institutes should extend their collaborations, begun with MEP staff embedded at nine institutes, to include all of the institutes.

Federal and state leaders should create and fund additional public-private partnerships to extend SMEs' access to high-cost manufacturing equipment in shared facilities and to high-performance computing applications.

Government at all levels should continue to advance efforts to use Total Cost of Ownership (TCO), rather than unit price, in purchasing decisions. Similarly, use of Value Engineering should be extended beyond DoD to all government agencies.

EDUCATIONAL INSTITUTIONS

Community colleges, vocational schools, and high schools, in collaboration with local industry and community development programs, should replicate and scale nationwide successful practices in education and skill development that provide good jobs for workers and trained staff for employers.

Educational institutions should extend opportunities for engineering and business students to work with smaller manufacturers. Cooperative education programs, the DoE's Industrial Assessment Centers, and the National Science Foundation's Advanced Technological Education (ATE) program are examples of formal programs, but individual schools should encourage more student interaction with manufacturers.

Community colleges, high schools and training intermediaries should engage with the Manufacturing USA institutes to design and train for careers that make use of the new technology developed at the institutes. NSF's ATE program provides an instructive model.

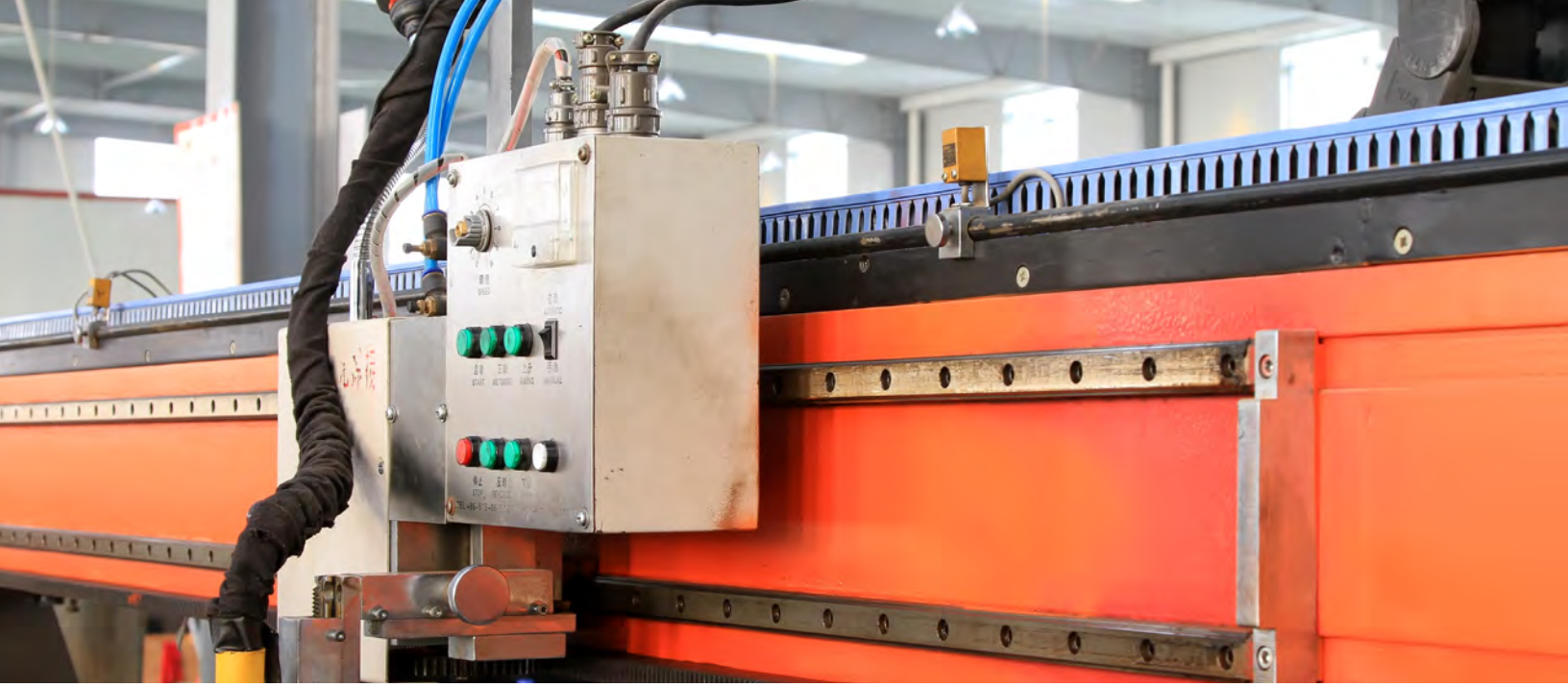
RESEARCHERS

Continued translational research, such as that conducted at the Manufacturing USA institutes, is essential for long-term progress in developing and commercializing advanced manufacturing technologies.

Multidisciplinary research is essential for widespread implementation of all the data-driven technologies inherent in next-generation supply chains. Issues such as data integrity, cybersecurity, privacy, ownership rights, and even liability all need to be addressed to identify best practices and implementation strategies that will ensure wide acceptance and rapid dissemination.

Research in business and management practices will be essential to help managers within and between firms design management structures that promote collaboration and innovation in supply chains.

Policy informed by rigorous economic research can promote implementation, minimize the negative disruption, and ensure the broad-based prosperity that next-generation supply chains can help achieve.



INTRODUCTION

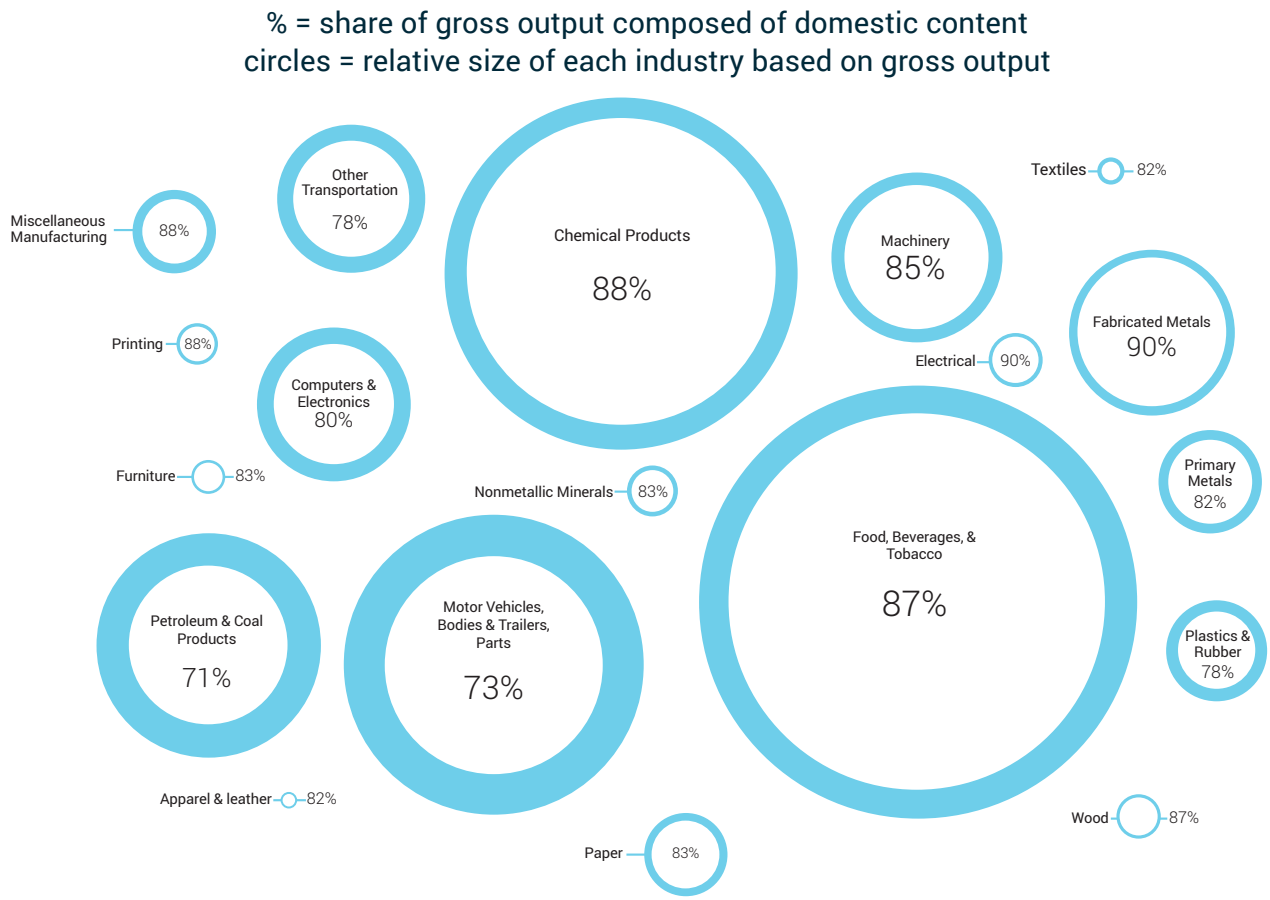
A small manufacturer of multi-touch control panels started in Chicago. As sales grew, the young firm needed to expand production, a significant capital investment. Considering its options, it became clear that shifting production to China was the only viable choice, for two reasons: supply chain and financing. Its panels are components in larger products, nearly all of which are made in China. Co-locating their production with final product manufacturers eliminated shipping costs and facilitated joint troubleshooting. Raising the capital needed to finance expansion in the United States was difficult for a small hardware company, but the firm's Chinese partner agreed to build additional production capacity. By expanding production in China instead of the United States, the Chicago firm increased sales and simplified its supply chain. Its Chinese partner made it easy. Similar stories, repeated in multiple industries, illustrate the challenges facing U.S. manufacturing.

[5] Don Norman, address to "Workshop on Building the National Network for Manufacturing Innovation," National Academy of Engineering, Sept. 27, 2012.

Responding to challenges creates opportunities. Although rapid and extensive globalization has eroded the domestic manufacturing base resulting in fewer companies and fewer employees, continued progress in manufacturing-related technologies—advanced materials, additive manufacturing, automation, sensors, predictive analytics, and more pervasive information technology—are creating new opportunities for U.S. manufacturing. At the same time, management practices that recognize the importance of suppliers and enable effective collaboration among multiple suppliers are becoming more popular. Effective implementation of appropriate technologies and effective management of end-to-end supply chains will give U.S. manufacturers a competitive edge in the global market.

The role of supply chains in overall manufacturing competitiveness has been the subject of multiple studies in recent years. Many analysts argue that **global competition is no longer between companies, but between supply chains.** For manufacturing performed in the United States, typically greater than 80 percent of gross output is domestic content, meaning U.S. suppliers are especially important to the overall health of domestic production (see Figure 1). In particular, the role of small and medium-sized enterprises (SMEs) in supply chains has been recognized as critical to manufacturing success. **Almost one quarter of the value of U.S. manufacturing comes from SMEs, which employ greater than 40 percent of manufacturing employees,** a steady increase since 1980.[6]

FIGURE 1. DOMESTIC CONTENT IN U.S. MANUFACTURING INDUSTRIES, 2015[7]



[6] For example, see The Executive Office of the President and the U.S. Department of Commerce, *Supply Chain Innovation: Strengthening America's Small Manufacturers*, March 2015. This paper defines SMEs as firms with 500 or fewer employees, similar to the Small Business Administration definition.

[7] U.S. Department of Commerce, Economics & Statistics Administration, "2015: What is Made in America?" March 2017.

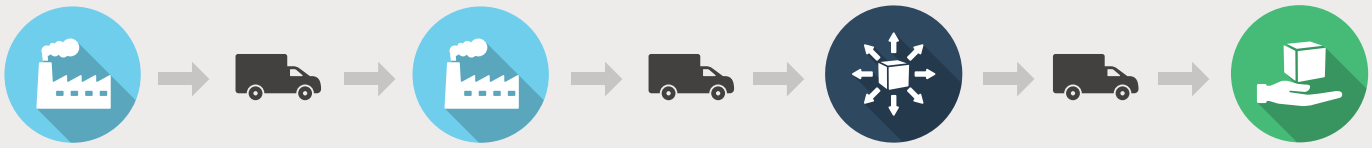
Census data indicate that supply chains on average account for two-thirds of a manufacturer's total costs of doing business.[8] **Understanding the importance of supply chains is key to crafting effective policies and investment strategies, both private and public, to realize the promise of advanced manufacturing.**

Supply chain management is a long-standing field of research and practice, focused largely on procurement, logistics, warehousing, and distribution.[9] Innovation in these aspects of supply chain management has led to significant efficiencies. There are also exciting opportunities in the interactions among suppliers and customers in design and manufacturing. **Integrated information systems, modeling and simulation, virtual prototyping and production testbeds, and numerous other cyber-physical systems are moving from research laboratories and high-value production floors to become accessible and affordable to more companies. The capabilities provided by these technologies, often collectively referred to as Industry 4.0,** will have profound impacts on supply chains, especially the expectations placed on SMEs. Management practices that value contributions throughout a supply chain are becoming more common, with the best companies striving to optimize their entire value chain; evidence is mounting that these firms are more profitable and innovative. Combining these effective engineering tools and management practices with emerging information and operational technologies will create a more competitive, innovative national manufacturing sector. Achieving this vision poses multiple challenges that will require coordinated, consistent effort by company managers, government policymakers, researchers, and educators.

This report will focus on these design and manufacturing aspects of supply chains. After a brief description of different types of supply chains and the factors driving their performance, the report will address the challenges facing companies throughout these chains, making clear the inability of market forces alone to generate the incentives necessary to achieve the strategic vision of a strong, competitive U.S. manufacturing sector. Finally, recommendations applicable to government, educational institutions, researchers, and the private sector will be presented.

[8] Susan Helper and Timothy Krueger, Supply Chains and Equitable Growth, The Washington Center for Equitable Growth, Sept. 2016, at http://equitablegrowth.org/report/supply-chains-and-equitable-growth/.
[9] The Institute for Supply Management (ISM) began in 1915 and has published the Manufacturing Report on Business monthly since 1931.

FIGURE 2. A SIMPLE LINEAR SUPPLY CHAIN



TYPES OF SUPPLY CHAINS

Every manufacturer buys from and sells to another company or final consumer. This chain of buyers and sellers varies by product and industry. Most simply, a supply chain is a series of specialized buyers and sellers each adding incremental value to a final product (see Figure 2).

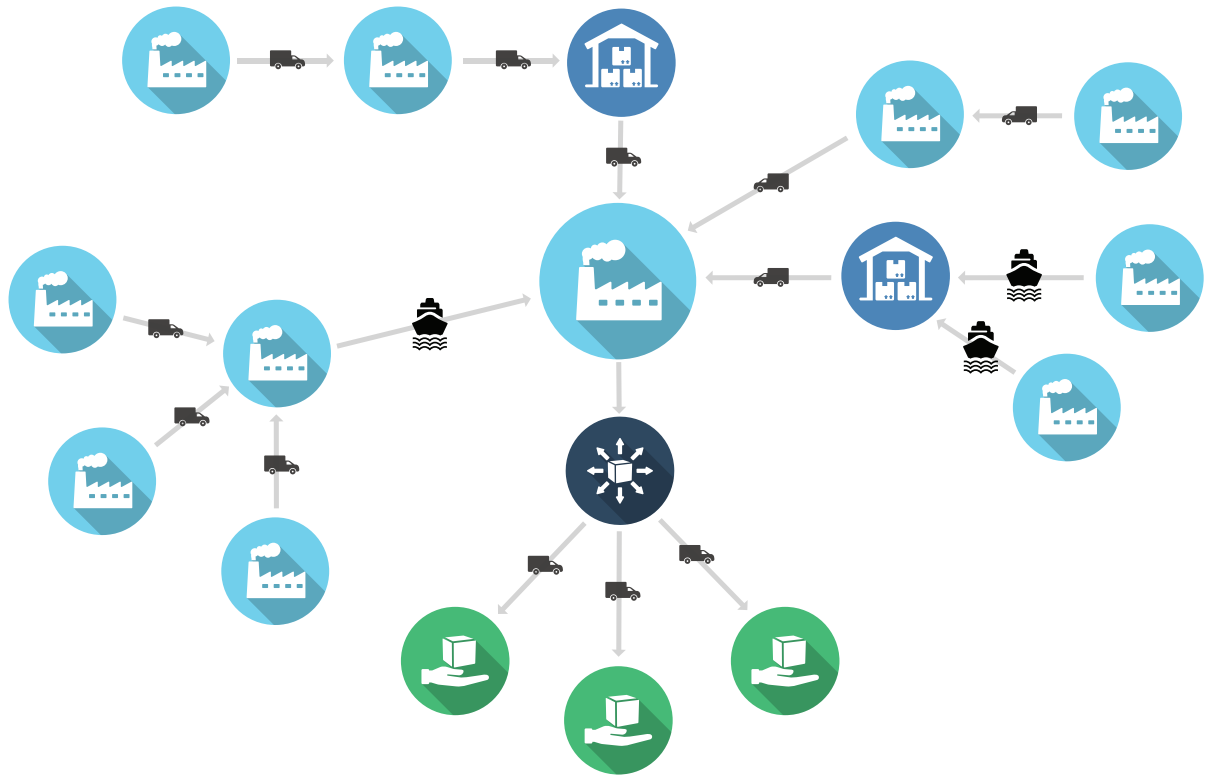
The nature of the product influences the form and size of the supply chain. Engineering dictates the sequence of production steps and, therefore, movement of incremental production along the supply chain. More complex products tend to require more complex supply chains, including production of subcomponents by subsets of suppliers within the chain. Frequently, suppliers serve multiple (sometimes competing) buyers; this is especially true when the supplier is a distributor, aggregating parts from its own network of manufacturers. As the networks spread to smaller suppliers, the buyer making the final product—commonly called the original equipment manufacturer

(OEM)—often has no direct knowledge of those suppliers, which comprise the lowest tiers in the supply chain. Adding to the complexity, large buyers making final products in some markets sell to even larger buyers selling in other markets. These multiple and complex relationships have been described as spider networks (see Figure 3).[10]

Some business analysts have described differences in supply chains based on relationships among the companies in the chain, resulting in five categories:

1. **The simplest supply chains are governed by markets**, with buyers and sellers exchanging goods primarily on the basis of price along with acceptable quality and delivery expectations; little additional information is exchanged. Commodity parts such as nuts and bolts, many packaged goods, and basic apparel items are examples.
2. **Modular** supply chains are also price driven, but depend on suppliers manufacturing to their customers' specifications. Examples include fashion apparel, designer furniture, and power tools.
3. **Relational** chains are based on strong relationships among suppliers characterized by long-term interaction, trust, and knowledge sharing. Relational supply chains are frequently associated with industrial clusters, geographic groupings of related firms that benefit from proximity. Medical devices in Minnesota and aerospace in the Seattle region are examples.
4. In **captive** supply chains, suppliers depend on long-term relationships with a dominant buyer. The pharmaceutical industry is an example. Because changing suppliers is difficult due to

FIGURE 3. COMPLEX, MULTI-POINT SUPPLY CHAINS



[10] Richard Baldwin and Andrew Venables, "Spiders and Snakes: Offshoring and Agglomeration in the Global Economy," *Journal of International Economics*, vol. 90, 2013, pp. 245-254.

regulatory requirements, large pharmaceutical companies typically build long-term relationships with many of their suppliers.

5. **Hierarchical** supply chains are characterized by significant vertical integration or other mechanism for the lead firm to exert managerial control.[11] Toyota, with ownership shares in many of its suppliers, is an example.

Another system for classifying relationships in supply chains is based on the volume and value of the firm's production (see Figure 4). Commodity firms in the lower right quadrant produce large numbers of low value parts; these would typically be commodity parts with low barriers to entry and many alternative suppliers. These suppliers compete based on price and delivery (a market relationship) and have little if any leverage with their customers. Examples include standard fasteners, brackets, tubing, cans, and other commodity products.

Standard firms in the lower left quadrant produce low volumes of low-value inputs. These parts have standard specifications and common production methods, with multiple competitors. Suppliers tend to have many customers, but little leverage with any. Examples include some medical supplies, trailers, and some types of machinery.

Specialty part suppliers in the upper right quadrant manufacture high volumes of high-value parts. Production processes tend to be more specialized, requiring tighter tolerances, use of special materials, high capital costs, or unique skills that create barriers to entry. These parts tend to be strategically important with relatively few alternatives, thereby generating market power for the suppliers. Computer processing units (CPUs) and flat glass for electronic displays are examples.

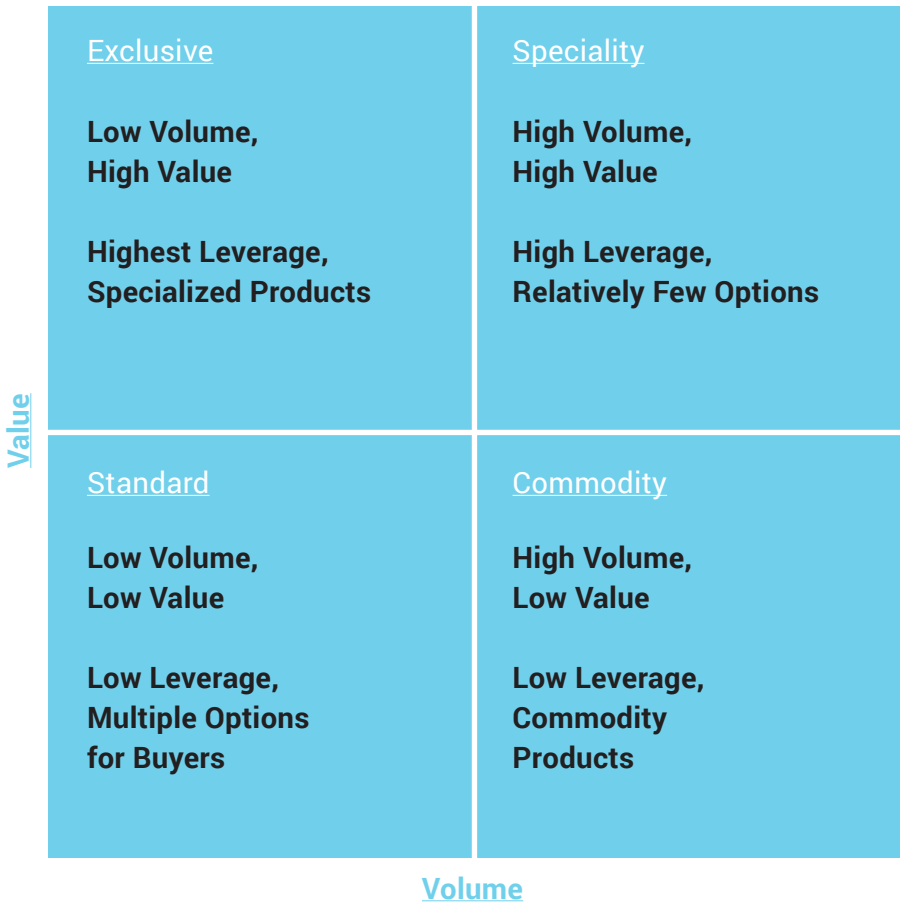
Exclusive suppliers in the upper left quadrant produce low volumes of high-value products. These firms tend to have a specialized niche that may be based on proprietary designs or production processes. Firms in this quadrant have few substitutes and can exert monopoly power, at least in the small niches they occupy. Examples include precision components in prosthetics and medical instruments.

Focusing on Specialty and Exclusive markets tends to produce more competitive production and higher profitability, and there is evidence that U.S. manufacturing is shifting toward those quadrants, producing higher value products with more leverage in the market.[12] However, often the buying firm's strategy, not just the characteristics of the part being produced, determines which quadrant a supplier occupies. For example, a lead firm may recruit new entrants to an industry in order to reduce existing suppliers' market power, or may choose a premium version of a product, perhaps reducing the number of firms that can provide the parts.

These descriptions of supply chains and suppliers have implications for real-world supply chain management. Examples from the automotive industry, probably the most studied supply chain, are instructive. The automotive industry produces a complex product from sub-assemblies and parts procured from hundreds of suppliers. The most outsourced parts of a vehicle include interior systems, door panels, fuel systems, braking systems, and steering systems. Note that the number of suppliers used by individual U.S. automakers has fallen dramatically in recent decades as the principles of lean production, quality systems, and continuous improvement have pervaded the industry.[13] Even so, relationships with suppliers

[11] Gary Gereffi, John Humphrey, and Timothy Sturgeon, "The Governance of Global Value Chains," *Review of International Political Economy*, vol. 12, no. 1, 2005.
[12] Timmer, Marcel, Abdul Azeez Erumban, et. al., "Slicing Up Global Value Chains," *Journal of Economic Perspectives*, vol. 28, no. 2, Spring 2014, pp. 99-118.

FIGURE 4. VALUE x VOLUME MATRIX



span multiple quadrants with varying levels of control. Automotive supply chains fit the spider model, in which some suppliers work with multiple OEMs, others work only with large Tier 1 and Tier 2 suppliers that manufacture sub-assemblies, and still others sell to distributors and may not realize they are ultimately supplying an automaker. History as well as technology can influence supply chain relationships. For example, it has taken decades for U.S. automakers to adopt the lean production practices embodied in the Toyota Production System throughout their supply chains. **Building appropriate relational contracts—agreements to collaborate long-term—with suppliers proved to be especially difficult after a history of short-term, adversarial relationships.**[14]

[13] The number of North American automotive suppliers declined from an estimated 30,000 in 1990 to less than 5,000 in recent years due to a combination of lean production, vehicle design, and consolidation in the industry. See, Office of Transportation and Machinery, International Trade Administration, U.S. Department of Commerce, "On the Road: U.S. Automotive Parts Industry Annual Assessment, 2011."
[14] Susan Helper and Rebecca Henderson, "Management Practices, Relational Contracts, and the Decline of General Motors," *Journal of Economic Perspectives*, vol. 28, no. 1, Winter 2014, pp. 49-72.

EVOLUTION OF SUPPLY CHAIN MANAGEMENT

Over the past three decades, manufacturers have unwound vertical integration, expanded their supply chains globally to take advantage of low wages, and focused on core competences.[15] While supply chains expanded geographically and in complexity, manufacturers increasingly recognized supply chains as a source of competitive advantage. For many, benefits of suppliers in low-wage locations overwhelmed the additional costs of transportation, the risks of disruptions, and loss of control over critical manufactured inputs. Efforts were made to minimize risk, for instance by requiring suppliers to comply with quality standards such as ISO 9001 and AS 9100, requiring other industry-specific certifications, and imposing strict delivery and other performance requirements. A few examples are instructive:

[15] C.K. Prahalad and Gary Hamel, "The Core Competence of the Corporation," *Harvard Business Review*, May-June 1990.

- Quality standards, such as ISO 9001, TS 16949 (used by the automotive industry), and AS 9100 (used by the aerospace industry), provide the basis for rigorous quality management systems in both small and large manufacturers. In many supply chains, being registered as ISO and/or AS compliant provides buyers with a level of confidence that the supplier has consistent, rigorous processes to ensure high-quality production with minimal defects. For many large companies, having a certified quality system is a requirement to be considered as a supplier.
- Six Sigma has become increasingly common as a method to improve quality by removing the causes of production defects and minimizing variability in manufacturing processes. It uses statistical methods to improve quality with the goal of achieving 3.4 defects per million. Few companies achieve this goal, but use the tools of Six Sigma and progress toward the goal to instill a culture of continuous improvement, to reduce costs, and to add value for themselves and their customers. Proficiency in Six Sigma methodologies is an attractive selling point for many suppliers, large and small.
- The Supply Chain Operations Reference (SCOR) model is a cross-industry standard diagnostic tool for supply chain management. The model describes the activities needed to satisfy customer demand, provides a basis to benchmark and quantify operational performance, and has generated a set of best practices used by companies to improve their supply chain management.
- Materials Management Operations Guidelines/Logistics Evaluation (MMOG/LE), introduced in 2002 in the automotive industry, is a self-assessment tool designed to evaluate suppliers' production, material handling, service, and logistics processes. As automotive OEMs have incorporated lean production principles and just-in-time (JIT) delivery practices to minimize parts inventory, MMOG/LE helps improve confidence that suppliers can meet the demands of a JIT environment. Many automotive OEMs, including Ford, General Motors, Fiat Chrysler, Volvo, and Renault, and Tier 1 suppliers require suppliers to use it and to update it annually. Many users report significant improvements in inventory costs, shipping costs, and delivery performance.[16] The latest version, Version 4, includes emphasis areas on sustainability, risk management and alignment of supply chain strategy with business strategy.

These and other tools used by large customers increase their confidence in and real-time knowledge of supplier performance; in many cases, they are imposed as requirements on the suppliers with little or no assistance from the large customer. Suppliers may be told to become either ISO or TS compliant or lose that customer's business. How they achieve compliance is up to them, which can place a significant burden on small suppliers. Imposing these requirements illustrates a fundamental contradiction in typical large customer/supplier relationships: most buyers continue to focus on short-term metrics such as lowest cost, on-time delivery, short lead times, and cash, while also expecting suppliers to invest in training, quality systems, and the technology needed to meet quality, delivery, and cost demands. **Fortunately, some resources, such as the Hollings Manufacturing Extension Partnership (MEP), have been available to help smaller suppliers implement quality systems and other requirements needed for their**

[16] Note that OEMs may impose strict fines on suppliers that fail to meet their JIT delivery requirements causing the assembly line to stop. See, Peter Waldman, "Inside Alabama's Auto Jobs Boom: Cheap Wages, Little Training, Crushed Limbs," *Bloomberg Businessweek*, March 23, 2017.

participation in supply chains, an example of the key role of government in maintaining and growing an effective, competitive supply base.

Although this arms-length approach to managing supplier relations remains prevalent in most industries, leading firms have recognized two important developments: 1) suppliers are an increasing source of their overall competitiveness, and 2) imposing certification requirements does nothing to differentiate their supply chains from competitors' or to extract more value from suppliers to raise the performance of the entire multi-company ecosystem. This recognition has caused a growing number of companies to realize that this approach to managing suppliers, focused on cost, delivery, and minimum quality standards, is insufficient to achieve long-term growth, flexibility, innovation, and profitability goals. **The cost/benefit calculus has started to change as more domestic manufacturers recognize the benefits of closer relationships with a smaller number of suppliers that are treated as a source of value and innovation** (see BAE Systems box).

How this shifting calculus is implemented operationally varies by industry and product characteristics, but a generally accepted set of best practices for optimizing supply chains is emerging among leading firms in multiple industries. Long-term competitiveness of large and small U.S. manufacturers depends on diffusing these practices throughout the manufacturing ecosystem as quickly as possible, enabling more innovation, taking advantage of emerging technologies, and avoiding being left behind by foreign competitors.

SUPPLY CHAIN OPTIMIZATION

Supply chain optimization (SCO) is the term commonly used for these emerging best practices. SCO extends the tools long used

BAE SYSTEMS

BAE Systems' Controls & Avionics Solutions (CAS) business in Fort Wayne, Indiana, manufactures electronic controls for the aerospace industry. Winner of the Shingo Prize in 2005, the Fort Wayne plant has long been a leader in implementing lean manufacturing principles and managing suppliers as part of its total lean production process.

At this facility, supplier relationships are managed by Sourcing Engineers—degreed engineers with full responsibility for purchasing, contract administration, expediting, inventory planning, value engineering, and supplier quality engineering. All of the traditional silos found in most manufacturers were consolidated in the Sourcing Engineers, who are integral to manufacturing operations. They are empowered to work with suppliers to ensure quality, delivery, cash management, and cost meet and exceed expectations.

To achieve operational excellence and a zero-defect culture throughout the supply chain, BAE Systems recently introduced its "Partner 2 Win" supplier performance program. The program has multiple elements. Sourcing Engineers take the lead in conducting supplier business reviews. A 12-month rolling scorecard focused on quality and delivery performance is compiled monthly, giving suppliers a quality score and a delivery score that can be compared with peers. Gold, silver, and bronze ratings are given to high performers. If the monthly score falls out of historic norms, specific causes can be addressed immediately. When necessary, Sourcing Engineers will work at suppliers' facilities to help them solve problems, and pull in additional technical help from BAE Systems if needed. High performers are rewarded with more business, to grow along with BAE Systems. Tim Eubank, Director of Supplier Partnerships for the CAS business area, noted, "The contribution of our supplier partners continues to become more and more vital to our performance for our ultimate customers. Initiatives like Partner 2 Win are key for our collective success."

In addition to the constant interaction with suppliers from the scorecards, BAE Systems also created a 10-member supplier advisory council, holds an annual supplier symposium, conducts a supplier perception survey, and holds periodic supplier workshops. All of these mechanisms provide suppliers with opportunities to contribute ideas to the total lean production process, to work together with BAE Systems on continuous improvement in cost, quality, and delivery, and to reinforce that their contributions are both valued and expected.

to ensure reliable supplies to include more integrated design and engineering practices, greater information sharing, and more proactive management practices to capture and share value. Leading firms begin with a strategic vision of their total manufacturing ecosystem, including a well-defined set of critical objectives and a desire to minimize risks to critical inputs while maximizing the value contributed by suppliers. The most successful OEMs take steps to eliminate or minimize the internal silos that prevent effective communication between functions such as engineering, manufacturing, and procurement, and often result in suboptimal decisions for the company as a whole. These internal organizational changes enable large firms to apply best practices in their relations with suppliers (see Johnson & Johnson box). Best practices include:

Supplier Partnering: Recognizing the value that suppliers can add, large customers are changing their contracting patterns to include more cooperative provisions. These top tier companies consolidate the number of suppliers to create long-term relationships, work jointly to set quality and life-cycle cost targets, and share in new product development. The number and frequency of contracts are often reduced and payments are no more than 30 days, a key to ensuring working capital and cashflow are conducive to supplier performance. With confidence that their customers are engaged with them, suppliers become innovation partners, not just fillers of purchase orders.

Total Cost of Ownership (TCO): Rather than focusing on initial price—and typically expecting continued price reductions from suppliers—leading companies work with suppliers to understand the TCO over time for parts and assemblies. TCO empowers manufacturers to make strategic buying decisions by including financial calculations for each activity in the supply chain: materials, design and engineering, production, transportation, storage, distribution, and final sales. Calculating TCO provides a metric to understand the value of working with suppliers on part designs and material selection and the costs and benefits of using local suppliers (often called proximity sourcing) to avoid the time, expense, and risk of transportation. Use of TCO can provide a powerful argument for increasing production in the United States.[17]

Design for Manufacturing (DfM): Suppliers often have greater knowledge of manufacturing processes for their output than their customers. Smart customers recognize and incorporate this knowledge into their design process, working with suppliers to refine part designs for more efficient production and modify assemblies for fewer parts and easier assembly.

Value Analysis/Value Engineering (VAVE): Similar to but more comprehensive than DfM, VAVE involves extensive interaction between customers and suppliers on design and manufacturing issues with the objective of maximizing value to both parties. In the automotive supply chain, the share of suppliers contributing to part designs rose from 48 percent in 1989 to 70 percent in 2011.[18] Because of its proven effectiveness, federal departments and agencies are required to establish and maintain cost-effective VE procedures to reduce acquisition and life-cycle costs.[19]

Model-based Enterprise Environment (MBE): Related to DfM and VAVE, MBE is a production system that uses electronic, interoperable engineering modeling tools to optimize design, manufacturing, and supportability. The resulting 3D models are comprehensive,

[17] Many TCO calculators are available on the internet, including calculators for buy vs lease and local vs offshore production decisions.
[18] Susan Helper and Jennifer Kuan, "What Goes on Under the Hood? How Engineers Innovate in the Automotive Supply Chain," Working Paper 22552, National Bureau of Economic Research, August 2016, p. 11.
[19] See Federal Acquisition Regulation parts 48 and 52.248 and OMB Circular A-131.

JOHNSON & JOHNSON

Johnson & Johnson is an example of a complex, large organization in the process of evolving the culture to embrace more innovation and fewer silos in its supplier relationships. In its pharmaceutical business, cost, quality, and delivery remain baseline requirements for suppliers, but suppliers are encouraged to innovate, minimize risk to Johnson & Johnson, and practice sustainability.

Johnson & Johnson supports supplier innovations if there is a business case, and will pay a premium to innovative suppliers if the benefits are worth it. If Johnson & Johnson's customers will benefit, the business case is easier to make and change moves faster. Innovations from suppliers that achieve faster market response, faster cycle times, new markets, and greater customer satisfaction are emphasized. Sometimes suppliers innovate in creating new, substitute materials, either for products or packaging, but in the pharmaceutical business, innovations more often emerge in process innovation to drive value through yield improvement and operational upgrades. Process innovation could result in fewer ingredients, shorter lead times, or faster cycle times. Innovations in packaging include bottles with sensors for better product tracking, new bubble packs for improved product security, and other upgrades to improve outcomes for customers.

Changing suppliers in the pharmaceutical industry is difficult because of the regulatory environment, so long-term relationships are common. Johnson & Johnson works directly with suppliers to maintain performance and avoid complacency. Regular supplier assessments are done by a cross-functional team led by the procurement office with expertise in manufacturing, quality, R&D, chemistry, and packaging. Working collaboratively with the supplier, the assessments are used to develop corrective action plans, including training. Quality and Environment, Health, and Safety (EHS) are areas where Johnson & Johnson shares its expertise directly.

Johnson & Johnson strives to be proactive in mitigating risk in its pharmaceutical supply chain. A risk management Center of Excellence assesses risk based on spending levels, the age of the relationship, how critical the supplier is, and the supplier's history of innovation. Factors such as financial stability, plant closures, number of production accidents, and reliability of transport are used to determine the level of risk a supplier may pose to Johnson & Johnson's production. The key is having sufficient information about suppliers deep in the supply chain, which depends on suppliers sharing information. Long-term relationships help, but visibility remains a challenge, even with new information systems, such as Elementum, used by Johnson & Johnson.

with all the information that suppliers need for manufacturing, thereby decreasing lead times, reducing engineering changes, and improving quality. Though becoming more common, widespread use of MBE remains constrained by the ability of SMEs to accept and use the models directly rather than convert them to 2D drawings.

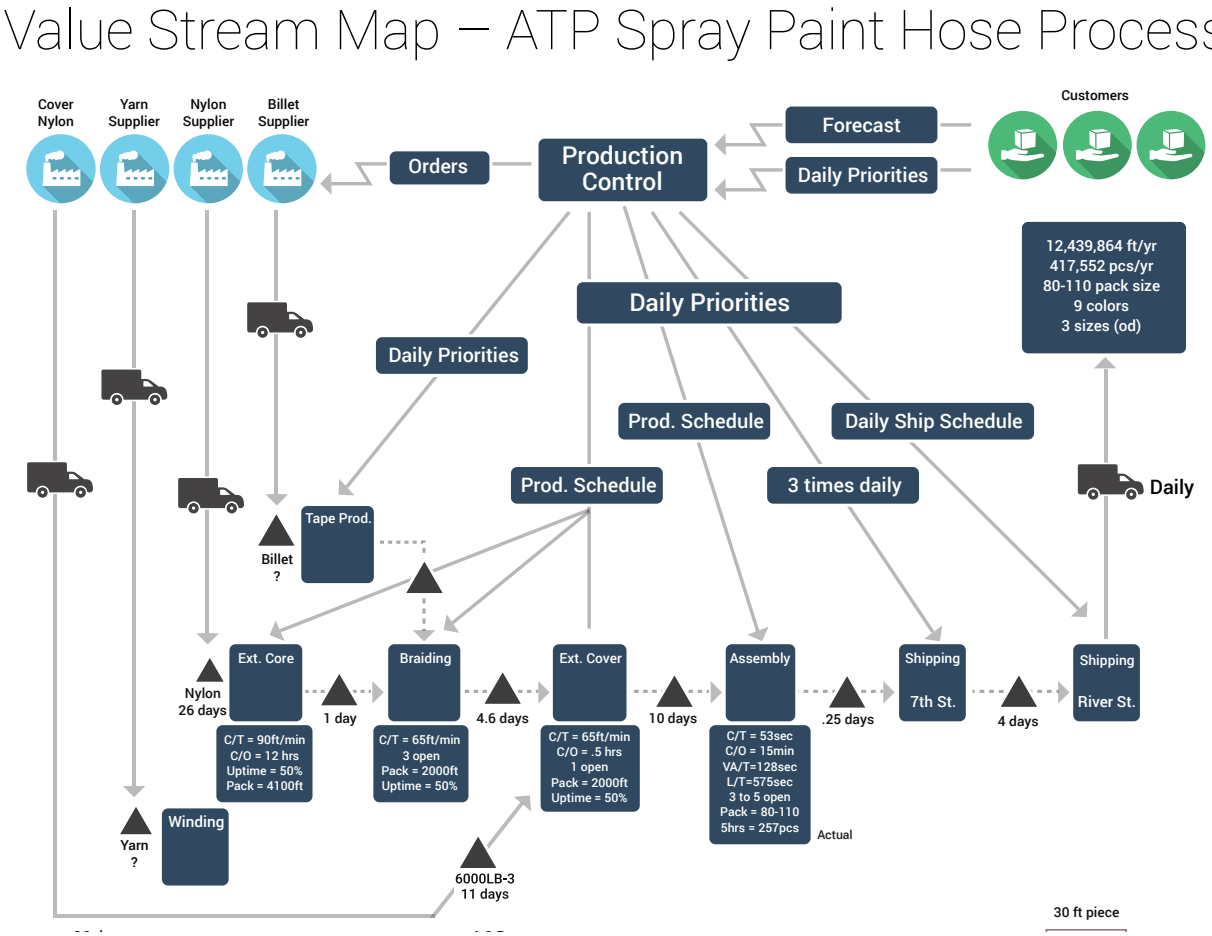
Theory of Constraints (ToC) is another tool used to expose bottlenecks within an individual production facility and across a supply chain. Developed by Elihayu Goldratt and taught extensively in business and engineering schools, ToC provides a methodology to identify constraints in a system that need to be changed, determining what the change should be, and then deciding how to implement the change.[20]

Value Stream Mapping (VSM) creates easy-to-read diagrams of the value added by multiple inputs to a production process. The value stream maps help to visualize the sequence and timing of input flows, dependencies among inputs, and potential bottlenecks. Used for years to map value streams within a single facility, manufacturers now map across multiple suppliers to increase visibility and improve decision making throughout the supply chain. Multi-functional teams map how parts and production flow through the existing total manufacturing process, identify gaps and bottlenecks, then produce a "future state" VSM identifying changes needed for more efficient production. Figure 5 provides an example of a current state value stream map.

Rapid Response Factories: With sufficient and timely information on final customer demand, manufacturers in industries such as fashion have implemented agile, quick response factories with flexible production lines that depend on flexible, responsive suppliers. Inventory levels

[20] The principles of ToC were first expounded in E.M. Goldratt, *The Goal*, first published in 1984.

FIGURE 5. CURRENT VALUE STREAM MAP[23]



are kept low while the level of trust in the supply base is high. Zara, a Spanish fashion company, established rapid response factories in Spain, close to its main European markets, to minimize inventory and shipping times to respond quickly to changing demand.[21]

Enterprise Resource Planning (ERP): ERP software has become more pervasive and more capable since its emergence in the early 1990s, and is now a multi-billion-dollar business led by firms such as SAP, Oracle, Microsoft Dynamics, and SysPro. ERP is business management software that includes production planning, manufacturing, marketing, inventory and materials management, and other business functions. Supply chain management has become a popular supplement to ERP systems, providing greater, albeit still incomplete, visibility into supply chain production, schedules, capacity, and inventories. To make this supply chain management function more accessible to smaller suppliers, an increasing number of vendors offer low-cost, software-as-a-service (SaaS), cloud-based ERP systems that can communicate with systems used by OEMs. Exostar, created by a consortium of aerospace companies, provides a web-based interface where OEMs and suppliers share production data easily and securely.[22]

[21] Alain Vix, "Going for Supply Chain Gold," *Lean Management Journal*, March 2012.
[22] See https://www.exostar.com/.
[23] Example VSM provided by private consultant.

End-to-End Supply Chain Planning: New capabilities in ERP systems, coupled with greater access to ERP software appropriate for SMEs, are beginning to provide greater visibility into total supply chains. Based on this improved, real-time information flow, OEMs can work with suppliers to increase flexibility of production and keep supply synchronized with demand, and to identify necessary redundancy in the supply chain to minimize the effect of disruptions. For example, a car seat manufacturer has a contract with an OEM that defines average output based on the supplier's capacity. Orders for a specific number of car seats are binding 3 days before delivery, but average weekly output can be increased 15 percent with 4 weeks warning, by 30 percent with 3 months warning, and by 40 percent with 6 months warning. In return for this flexibility, the car seat supplier gets full visibility of the OEM's production schedule.[24]

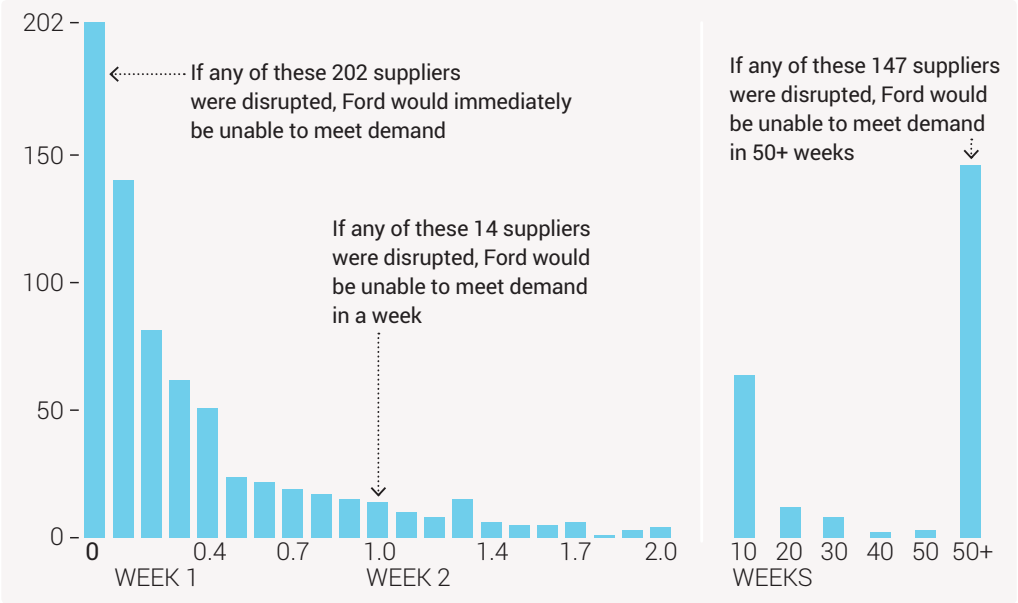
Risk Exposure Index (REI): Developed by David Simchi-Levi at MIT, the supply chain REI allows companies to quantify the risk posed by supply disruptions across their total value chain. The index uses calculations of Time to Recovery (TTR) for each disrupted supplier and the financial impact resulting from the disruption.[25] Ford used the REI to analyze its global supply chain in 2015, exposing two small but critical suppliers that could have disrupted Ford's production with big financial consequences (see Figure 6).[26]

FIGURE 6. SUPPLY CHAIN RISK EXPOSURE[27]

Time to Survive

A closer look at what a disruption could do to Ford's* supply chain.

NUMBER OF SUPPLIERS WITH A DISRUPTION IN INVENTORY SUPPLY



REMAINING WEEKS OF INVENTORY THAT WOULD ALLOW FORD TO MEET DEMAND

*DATA IS SLIGHTLY MODIFIED TO PROTECT PROPRIETARY INFORMATION
SOURCE DAVID SIMCHI-LEVI

[24] T. Ebel, K. Kubik, and M. Losch, "Light-footed Operations: The Virtues of Agility in Volatile Times," McKinsey & Co. at, http://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/ operations/pdfs/lightfooted_operations.ashx.
[25] Release of the REI is described at, http://www.prweb.com/releases/2012/3/prweb9259939.htm
[26] Leslie Sheppard, "MIT Forum and Infosys Risk Group release preliminary global risk survey findings," MIT Forum for Supply Chain Innovation, June 6, 2016.
[27] David Simchi-Levi, "Find the Weak Link in Your Supply Chain," *Harvard Business Review,* June 2015. Reprinted with permission.

Although all of these tools and management practices are used by some companies, few companies use them all and many companies have identified improving these areas as a critical performance gap. **One study identified 12 performance gaps affecting U.S. supply chains that included increasing the effectiveness of ERP systems, improving TCO decisions, improving OEM-supplier product development collaboration, reducing volatility, and mitigating risks.**[28]

RISK MANAGEMENT

The REI highlights a key element in supply chain optimization. As supply chains have become more complex, globally distributed, and dependent on technology, companies have become worried about increasing risk. **Based on the findings of MIT's 2015 Global Risk Survey, greater than 90 percent of respondents believe that risk is increasing, with supply chain complexity being their largest concern, followed by cybersecurity, business model disruption, and globalization.**[29] Data from the risk survey indicate that full recovery from a major supply disruption takes 2 years, with potentially large financial and market share impacts.

Figure 6 illustrates the risk of supply disruption in Ford's supply chain.[30] Based on its use of the REI, Ford discovered that disruption of supply from 202 suppliers would have immediate negative consequences. At the opposite end, Ford could survive more than 50 weeks of production if 147 suppliers were disrupted. The analysis enabled Ford to adjust inventory levels and reallocate resources to increase resiliency and minimize its exposure to supply chain disruption, ranging from natural disasters to technology failures to factory fires.

Another source of risk that has emerged with the growing use of information systems and digital tools in the supply chain is cybersecurity. Cybersecurity is a complex issue that is particularly relevant to supply chain management in two key areas. The first applies to integrated ERP systems and other forms of data sharing, such as digital prototypes and models. Because of resource and skill availability SMEs in the supply chain may have more legacy systems, less capability to track and implement security patches, and therefore tend to be the weakest cybersecurity links in the supply chain, which can compromise the entire chain. Flaws in digital designs can be difficult to identify and fix, yet can cause problems in production that compromise the integrity of the part and, therefore, the final product. Second, parts and components with digital sensors, control systems, and other features need to be secure when produced by suppliers to avoid insecure final assemblies.[31] Research is addressing both of these areas of cybersecurity, and government agencies such as the National Institute of Standards and Technology (NIST) and the Department of Homeland Security (DHS) provide resources to help companies reduce vulnerability, but the problems are complex and will continue to pose risks to supply chains. Every supplier with government work is expected to be compliant with Defense Federal Acquisition Regulations on cybersecurity by the end of 2017.[32]

[28] Genedge Alliance, "Enhancing U.S. Supply Chain Competitiveness," 2012.
[29] Leslie Shepard, MIT Forum for Supply Chain Innovation, at https://news.mit.edu/2016/mit-forum-infosys-risk-group-release-risk-survey-findings-0606.
[30] David Simchi-Levi, "Find the Weak Link in Your Supply Chain," *Harvard Business Review*, June 2015.
[31] MForesight will be releasing a report on cybersecurity in manufacturing in Spring 2017.
[32] DFAR clause 252.204.7008 requires compliance with NIST Special Publication 800-171 "Protecting Controlled Unclassified Information in Nonfederal Information Systems." It applies to organizations that process, store or transmit Controlled Unclassified Information (CUI). The deadline for compliance is December 31, 2017.

JUSTIFYING GOVERNMENT EFFORTS TO STRENGTHEN SUPPLY CHAINS

Cybersecurity illustrates the important role for government in strengthening supply chains. Government has historically played a significant albeit frequently reluctant role in supporting American manufacturing, and therefore, its supply chains. **U.S. policy emphasizes market forces to determine both company and national competitiveness, resulting in far less aggressive and comprehensive industrial policies compared to those implemented by other countries.**[33] However, imperfect markets create opportunities for U.S. policy initiatives to correct market failures, to address network failures, and to ensure strong supply chains needed to meet national security objectives.

[33]For a review of industrial assistance programs in other countries, see National Research Council, Board on Science, Technology and Economic Policy, *21st Century Manufacturing: The Role of the MEP Program*, Washington, DC: National Academies Press, 2013.

MARKET FAILURES

An important aspect of many supply chains is the asymmetry of market power and resources. Specialty and Exclusive companies in high-value markets, the top quadrants of Figure 4, have some degree of market power that provides resources for continued investment in advanced production technology, information systems, and skilled employees. Suppliers of lower value goods, particularly SMEs, have fewer resources available for equipment upgrades, information technology, or the workforce to operate advanced technology. **Market failures in the manufacturing ecosystem inhibit efforts to maximize value throughout the supply chain, hurting consumers, workers, and firms.** Market failures include:

- Price information alone fails to yield optimal resource allocations. Often OEMs and suppliers would benefit from jointly deciding on product and process design, but this information exchange often leads to relationship-specific investments that make one or both parties vulnerable to the costs of switching partners. Therefore, these investments are often not made.
- Monopoly (single seller) and monopsony (single buyer) markets are common. For example, OEMs can use monopsony power to manage their procurement to minimize the number of suppliers in the high-value quadrants of Figure 4.
- Manufacturers face a common pool resource problem. The local labor pool is small, companies are wary of training employees because higher skilled employees leave for higher wages elsewhere, and companies that can pay more often poach employees from competitors. The result is underinvestment in training, little upgrade in skills, and, frequently, technology stagnation. Cross-firm institutions, such as unions, that coordinated training in the past are weaker now.
- Concerns about free riders inhibit large buyers from providing technical and educational assistance to smaller firms in their supply chains because any improvement in performance could also help competitors that are supplied by that SME.
- Silos within powerful OEMs often lead to departments making decisions that benefit that department at the expense of the total OEM business. For example, finance departments sometime pay SMEs slowly to maximize cash flow, even though this practice results in higher costs for the OEM because SMEs face challenges gaining access to sufficient working capital. SMEs also have more difficulty accessing bank loans and tend to pay higher interest rates when loans are available.[34]
- The private consulting market fails to serve the needs of SMEs because there are high fixed costs to communicate with diverse, geographically dispersed manufacturing SMEs and low returns from the relatively small consulting projects that would result.

Overcoming these market failures is essential to more efficient supply chains and therefore to growing the U.S. manufacturing sector, which creates a critical role for government. Policies to strengthen manufacturing supply chains are mischaracterized as "corporate welfare" despite the benefits they produce for the rest of society.

NETWORK FAILURES

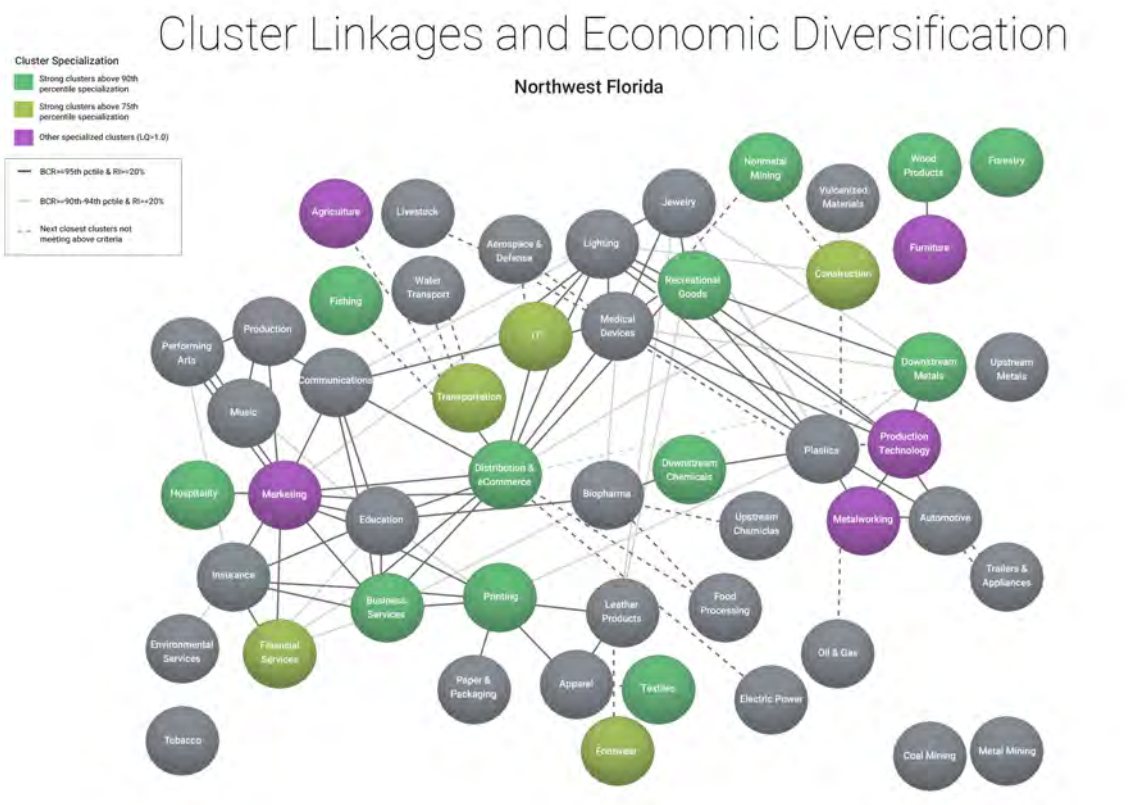
Market failures are not the only challenges facing SMEs. Network failures also inhibit access to information, people, new technology developments, and new business opportunities.[35]

[34] Susan Helper, Jessica R. Nicholson, and Ryan Noonan. *The Economic Benefits of Reducing Supplier Working Capital Costs*. U.S. Department of Commerce, Economic & Statistics Administration. November 2014.
[35] Andrew Schrank and Josh Whitford, "The Anatomy of Network Failure," *Sociological Theory*, no. 29, 2011, pp. 151-177.

Arguably, these network failures have become more important as large companies focus on core competences and extend their supplier networks to more diverse companies. Examples of network failures include:

- A deficit of information compromises efficiency. **Even with modern communication technology, no good options have emerged to match seller capabilities with buyer requirements beyond a small number of firms.** SMEs have limited access to information on new technology availability and prevalence beyond trade magazines and equipment sales representatives. Past attempts to create web sites, often called business portals, to provide easy access to the capabilities of multiple manufacturers have suffered from data inaccuracy over time. More recent attempts, such as the Supplier Connection and B2B Connect, may be more successful.[36] OEMs and Tier 1-2 suppliers have limited visibility into the full supply chain, increasing the risk of supply disruption and leading to inefficient resource allocation.
- Unbundling of production processes and other activities to focus on core competences may sacrifice scale economies that cannot be recreated by smaller suppliers. The suppliers, in turn, may increase their specialization but not have the resources to find complementary companies that could allow for new business opportunities.
- Cluster analysis has demonstrated the value of having a collection of companies in a particular industry located close to each other, supplying each other, and creating

FIGURE 7. EXAMPLE OF A REGIONAL CLUSTER MAP



[36] Supplier Connection is at https://www.supplier-connection.net; B2B Connect is at http://b2bconnect.me.

a pool of knowledge, talent, and skills that make the regional cluster more competitive and innovative. Because of these advantages, cluster analysis has become a mainstay of economic development.[37] Figure 7 illustrates a cluster map for northwest Florida. Smaller firms not located in clusters fail to benefit from these network effects, which are often informal and spontaneous.

NATIONAL SECURITY

Government intervention in U.S. manufacturing, though relatively limited throughout the post-War period, has most frequently been justified based on national security imperatives. Primary among these imperatives has been to ensure technological superiority to potential adversaries, which has driven an extensive research and development (R&D) capacity, focused on defense requirements but often with important and extensive commercial applications. Advanced materials, electronics, avionics, and communication and networking are obvious examples of defense research impacting the broader economy.

The importance of robust end-to-end supply chains for defense production cannot be overstated. Having a strong capability in every manufacturing process—from basics such as casting, welding, molding, and coating, to advanced such as lithography, precision machining, and additive manufacturing—is essential to defense production capability. Often these capabilities reside deep in the supply chain at SMEs. If anything, global competitive pressures have enhanced the need for government support for these SMEs to ensure that all manufacturing capabilities, as well as related strategic capabilities in advanced materials, microelectronics, telecommunications, and cybersecurity, are readily available in the defense industrial base.

[37] A partnership between the U.S. Economic Development Administration and Harvard Business School has generated extensive data and tools for cluster mapping, refined to county levels. See http://www.clustermapping.us.

GOVERNMENT INITIATIVES TO STRENGTHEN SUPPLIERS

Because of these inherent market failures and national security considerations, many federal agencies have programs to help small businesses and small manufacturers. A March 2017 study by the Government Accountability Office (GAO) identified 58 federal programs across 11 agencies that support manufacturing in some way.[38] Examples include longstanding programs, such as Small Business Development Centers and Procurement Technology Assistance Centers, that provide local help to small business, mostly non-manufacturers. The National Science Foundation has several programs designed to benefit industrial research and technology transfer, in particular the Engineering Research Centers and Industry/University Cooperative Research Centers, both of which include industrial partners but are not specifically targeted

[38] U.S. Government Accountability Office, "U.S. Manufacturing: Federal Programs Reported Providing Support and Addressing Trends," March 2017, at https://www.gao.gov/products/GAO-17-240.

at smaller manufacturers or supply chains. Programs that do target supply chains and work to upgrade skills, technology, and preparedness for the coming digital manufacturing ecosystem include the Manufacturing USA institutes, the Hollings Manufacturing Extension Partnership, and programs at the Department of Defense (DoD), the Department of Energy (DoE), and the Small Business Administration.

MANUFACTURING USA—THE NATIONAL NETWORK FOR MANUFACTURING INNOVATION

Recognizing the importance of advanced manufacturing to virtually every national objective—raising living standards, addressing trade imbalances, ensuring national security—the federal government established the National Network for Manufacturing Innovation program in 2014 with the public name, Manufacturing USA. The Manufacturing USA program is a network of manufacturing innovation institutes, each of which is a public-private partnership that brings together government resources, universities, and private companies to address specific advanced manufacturing technology areas. At present 14 institutes comprise the Manufacturing USA network (see following page).

MANUFACTURING USA INSTITUTES

The Manufacturing USA institutes could potentially play a key role in strengthening domestic supply chains. They provide hubs where large and small companies, universities, federal laboratories, and other relevant stakeholders can convene and collaborate to accelerate development and commercialization of advanced manufacturing technologies. Members have access to sophisticated equipment used to solve collective action problems while also developing specialized curricula to ensure the supply of skilled engineers and technical workers in the future. By pooling resources and fostering broad collaboration, within their technical specialties, the program addresses market and network failures, while accelerating technology development and commercialization in areas key to national security.

Industry and independent experts determined the technical focus of the institutes. The initial selection of technical areas was obtained through a crowdsourcing effort, including a federal Request for Information (RFI) and regional workshops beginning in April 2012. Input for more recent institute awards was collected through workshops, new RFIs, and open competition.

Although relatively new additions to the U.S. manufacturing ecosystem, **the Manufacturing USA institutes are having success building the extensive collaboration needed for development of their respective technologies.** Based on a recent review of the first eight institutes, nearly 1,200 organizations—companies, government agencies, nonprofits, and academic institutions—are linked through those institutes, creating more than 9,000 substantive relationships between organizations.[39] The institutes provide a mechanism to leverage the collective strength of all stakeholders in multi-level public-private partnerships, ultimately creating a shared experiential learning environment that would otherwise not be available. The institutes are especially important given the investments being made by other countries to advance technology development in various collaborative models.

[39] Deloitte, *Manufacturing USA: A Third-Party Evaluation of Program Design and Progress,* January 2017.

FIGURE 8. MANUFACTURING USA INSTITUTES

Advanced Functional Fabrics of America (AFFOA)

AFFOA works to enable a manufacturing-based revolution by transforming traditional fibers, yarns, and fabrics into highly sophisticated, integrated and networked devices and systems.

America Makes

America Makes is a national accelerator and leading collaborative partner for technology research, discovery, creation, and innovation in additive manufacturing and 3D printing.
Lead Organization: NCDMM

Digital Manufacturing and Design Innovation Institute (DMDII)

DMDII encourages factories across the United States to deploy digital manufacturing and design technologies, so those factories can become more efficient and cost-competitive.
Lead Organization: UI Labs

The National Institute for Innovation in Manufacturing Biopharmaceuticals (NIMBL)

NIMBL works to enable efficient and flexible manufacturing capabilities for existing and emerging biopharmaceutical products and develop a world-leading pharmaceutical manufacturing workforce.

American Institute for Manufacturing Photonics (AIM Photonics)

AIM Photonics works to accelerate the transition of integrated photonic solutions from innovation to manufacturing-ready deployment in systems spanning commercial and defense applications.

Advanced Regenerative Manufacturing Institute (ARMI)

ARMI will make practical the large-scale manufacturing of engineered tissues and tissue-related technologies, to benefit existing industries and grow new ones.
Lead Organization: DoD

The Institute for Advanced Composites Manufacturing Innovation (IACMI)

IACMI is committed to accelerating development and adoption of manufacturing technologies for low-cost, energy-efficient manufacturing of advanced polymer composites for vehicles, wind turbines, and compressed gas storage.

Power America

PowerAmerica is accelerating the adoption of advanced semiconductor components made with silicon carbide and gallium nitride into a wide range of products and systems.

Light Innovations for Tomorrow (LIFT)

LIFT is working to develop and deploy advanced lightweight modern metals manufacturing technologies.

Advanced Robotics Manufacturing (ARM)

ARM Institute's mission is to create and deploy robotic technology to realize the promises of a robust manufacturing innovation ecosystem.
Lead Organization: American Robotics

Clean Energy Smart Manufacturing Innovation Institute (CESMII)

Smart Manufacturing works to spur advances in smart sensors and digital process controls that can radically improve the efficiency of U.S. advanced manufacturing.
Lead Organization: Department of Energy

NextFlex

NextFlex's aim is to further U.S. development and adoption of the flexible hybrid electronics that will revolutionize the way we live, work and play.

Rapid Advancement in Process Intensification Deployment (RAPID)

The RAPID Institute convenes companies, universities, industrial research organizations and national laboratories to focus on new technologies that maximize processes at the molecular level to save energy with every chemical reaction

Reducing Embodied-energy And Decreasing Emissions (REMADE)

The goal of this institute will be to find new and less expensive ways to reuse, recycle, and remanufacture metals, fibers, polymers, and electronic waste.
Lead Organization: DOE

Germany's Fraunhofer Society, with 67 institutes and 24,000 staff, is one of the largest examples; Japan's Science and Technology Agency is another.

The America Makes institute provides an example of necessary and effective collaboration in its focus area, additive manufacturing. Membership includes more than 160 large manufacturers, SMEs, academic institutions, nonprofits, and government agencies. The collaboration made possible by this broad membership has allowed America Makes to address common research needs and issues such as standards that have wide interest in the technical community. For instance, working with the American National Standards Institute (ANSI), America Makes recently released a roadmap of existing and needed standards in additive manufacturing and identified specific R&D needed to meet the standards desired by industry.[40] As this example illustrates, Manufacturing USA institutes can play a critical role not only in conducting collaborative research in manufacturing technologies that are key to the future, but also in furthering other factors, such as standards, that are necessary for broad commercial adoption of these technologies.

THE HOLLINGS MANUFACTURING EXTENSION PARTNERSHIP

The Hollings Manufacturing Extension Partnership (MEP) at NIST in the Department of Commerce is the most extensive and comprehensive resource available to manufacturing SMEs. Since its founding in the late 1980s, the MEP program has expanded to include operations in all 50 states and Puerto Rico with a network of 600 locations and nearly 1,300 manufacturing experts. In FY 2016, MEP's $130 million federal appropriation was matched by $72.3 million in private funds (fees for services), $43.5 million in state and local contributions, and $44.1 million in other contributions. The program reaches 25,000 SMEs annually and provides fee-based services to 8,000.

MEP services include a range of technical, business, and managerial consulting and training that have helped manufacturers improve quality, implement lean production practices, upgrade information systems, and use computer-aided design and modeling/simulation technology. MEPs often find custom solutions to specific client problems, develop training curricula, and play a critical role in linking companies, universities, vocational schools, and other resources to build effective networks in a local manufacturing ecosystem.

Over the past 25 years MEP has been the subject of multiple independent assessments and academic analyses, as well as constant internal assessment based on independent surveys of the manufacturing clients of MEP centers. The overwhelming consensus of these various assessments is that MEP provides actionable help to the nation's small and medium-sized manufacturers that results in greater profitability, higher revenue, significant job creation and retention, and a higher level of investment and innovation than non-clients. The findings of the most recent assessment, by the Upjohn Institute, are indicative of MEP's impact on U.S. manufacturing. The authors' most conservative estimate of MEP's annual impact includes:

- 142,381 jobs added;
- An increase in gross domestic product (GDP) of $15.40 billion;
- An increase in national manufacturing output of $29.89 billion;

[40] See https://www.americamakes.us/news-events/press-releases/item/980-america-makes-and-ansi-publish-standardization-roadmap-for-additive-manufacturing.

- Personal income increased by $8.44 billion; and
- An increase in federal corporate income taxes of $1.13 billion.[41]

MEP fills an important gap in a foundational pillar of a strong manufacturing sector: the ability to work directly with small and medium-sized manufacturers and to provide access to information on technology advances and market opportunities that are important to SMEs' success.

Over the years, some of MEP's major initiatives have been aimed at strengthening supply chains and improving understanding of the importance of SCO to long-term competitiveness. Individual state MEPs have worked with large manufacturers in their region to support supply chain improvement through training programs, gap analyses, and product and process innovation. Because of market and network failures, the assistance available from MEP is the only readily available source of expertise and knowledge to help SMEs make specific improvements to become more competitive and relevant to potential customers. Currently, several MEP efforts are designed to improve supply chain performance, including:

SUPPLIER IMPROVEMENT

MEP has worked with individual suppliers within specific supply chains to help them meet the quality, cost, and delivery expectations of OEMs, including Boeing, Harley-Davidson, John Deere, Volvo, and BAE Systems. A current example is the Nissan Supply Chain Initiative Supplier Quality Development Program that focuses on specific quality issues within Nissan's existing supply chain. Led and developed by Tennessee MEP (TMEP), with service delivery including MEPs in Mississippi and Michigan, the program was launched in 2013. Nissan and TMEP worked together to develop a custom training program and implementation services to help suppliers meet Nissan's aggressive quality goals. Since 2013, TMEP and its partners have trained more than 1,000 people at more than 160 supplier facilities in 30 states.

SUPPLIER SCOUTING

MEP connects SMEs with supplier opportunities for OEMs, Tier 1 manufacturers and government agencies. Using its in-depth knowledge of SMEs and their capabilities, MEP has identified hundreds of potential domestic suppliers for more than $40 million in production opportunities that would have gone overseas.

SUPPLY CHAIN OPTIMIZATION

MEP's SCO initiative helps manufacturers build dynamic supply chains by developing a long-term strategy, increasing visibility throughout multiple supplier tiers, identifying and mitigating risk, identifying ERP systems that are compatible across supply chain tiers as well as appropriate and affordable for SMEs, and understanding TCO and other best practices that encourage strategic partnerships throughout the supply chain.[42] MEP's SCO projects often begin with a 2-day workshop that trains clients in specific techniques for developing a long-term vision for their company and its suppliers, then creates specific functional strategies to make the vision real, applicable, and executable.[43] Work that the Virginia MEP, Genedge Alliance, performed with Volvo Trucks and its suppliers (see box) is indicative of the benefits of SCO.

MANUFACTURING TECHNOLOGY ACCELERATION CENTERS (MTACS)

In 2014-15, MEP funded five pilot MTACs in California, Texas, Oregon, Wisconsin, and Georgia. Each MTAC focused on a different industry,

[41] Jim Robey, Randall Eberts, et. al., *The National-Level Economic Impact of the Manufacturing Extension Partnership (MEP)*, Kalamazoo, MI: W.E. Upjohn Institute for Employment Research, March 3, 2017, at http://research.upjohn.org/reports/226/.
[42] MEP provides specific training in TCO that includes use of a TCO calculator.

working with OEMs and suppliers, to understand the constraints facing suppliers in adopting advanced manufacturing technologies as well as the capabilities suppliers need to successfully implement specific technologies. For instance, the California MTAC began focusing on model-based engineering and design (MBE/MBD) in the transportation equipment supply chain. Over the course of the project, it transitioned to a focus on additive manufacturing and cyber-physical security because those were the highest priorities of the participating companies. Georgia focused on identifying technology needs and sources in the southeast automotive supply chain. Participants identified process technologies related to improved assembly operations as their highest priority and transitioning existing technologies from other industries, such as aerospace, as a promising source.

NORTHEAST REGION NEXT GENERATION SUPPLIER INITIATIVE

Building on the work of the National Supply Chain Network Initiative (NSNI) and MEP's work in SCO and supplier improvement, MEP centers in the Northeast are working together with several large OEMs to improve the performance of existing suppliers and to prepare new companies to join the supply chains. This multi-state initiative is being led by the MEP's Northeast Region in partnership with the NSNI and is intended to create a scalable model to connect SMEs and entrepreneurs to product and process innovations and markets. Combining the use of data bases, web portals, and existing resources with the field staff that MEP centers provide, the initiative includes a series of workshops that gather information about the current status of suppliers' manufacturing processes, quality systems, workforce skills, and use of technology. These assessments generate gap analyses—the gap between suppliers' capabilities and OEM expectations—and improvement plans that can then be implemented on site in suppliers' facilities. The initiative follows a model successfully implemented by Genedge Alliance in Virginia to upgrade the performance of suppliers to Volvo Trucks (see box). Lessons learned from this initiative will form the basis for MEPs national efforts to work more closely with multiple OEMs and their suppliers.

EMBEDDING AT THE MANUFACTURING USA INSTITUTES

The MEP system has placed MEP center staff members directly at nine of the Manufacturing USA institutes with plans to do so at the remaining institutes. The goal is to inform more SMEs about the resources available at the institutes and to diffuse the manufacturing technologies developed at the institutes more widely and rapidly into the supply base. For example, the Tennessee MEP has embedded two staff members at the Institute for Advanced Composites Manufacturing Innovation (IACMI) in Knoxville. In cooperation with MEP centers across the southeast region, the project will translate work being done at IACMI into a comprehensive outreach campaign and will develop a "train the trainer" program to educate suppliers in the region on the advantages and mechanisms of using advanced composites. In the program's second year, resources will be developed that can be used throughout the national MEP system to raise awareness of composite technology, and that can be used as a model for other Manufacturing USA institutes to increase awareness of their technologies. Finally, specific SMEs will be identified that are willing to work with MEP centers to implement technologies emerging from IACMI.[44]

[43] MEP Supply Chain Optimization client testimonials, at http://www.mepsupplychain.org/wp-content/uploads/2016/02/Handout_SCO-Client-Testimonials_2016-RevF.pdf.
[44] TMEP-IACMI Presentation for Project Launch, Dec. 12, 2016.

TECHNOLOGY COLLABORATIVES

Since 2013 NIST MEP has facilitated the development of eight regional Technology Collaboratives. The first of these successfully became the California Network for Manufacturing Innovation.[45] Since 2015, five regional Technology Collaboratives have been created in Indiana, Connecticut, Maryland, Tennessee, and Oklahoma, each with a different technology focus. Each includes primary stakeholders—regional universities and federal laboratories, state agencies, and a lead MEP center—and each works to raise awareness of available advanced manufacturing technologies and encourage transfer to the regional SME community. The overall goal of the Collaboratives is to develop and sustain regional innovation ecosystems and establish MEP centers as the premier source for information on advanced manufacturing technologies.

SUPPLY CHAIN CHALLENGES

Despite a strong record of assisting thousands of SMEs and a remarkably high return on investment to client companies and the federal and state governments that provide financial support, MEP faces challenges in its efforts to play an even stronger role in supply chain improvement. First, it is important to remember that MEP services are heavily influenced by market forces: MEP can only deliver services for which SME clients will pay. **This fee-for-service operating model is beneficial in ensuring that MEP centers are responsive to client demand and that clients value the services, but it also constrains MEP's ability to offer services that are more long-term, strategic, and proactive.**

Second, and related to the fee-for-service model, **several of the supply chain services outlined above—MTACs, Technology Collaboratives, and embedded staff at Manufacturing USA institutes—are based on specific grants**

[45] See http://www.cnmi.bz/.

SUPPLY CHAIN OPTIMIZATION AT VOLVO TRUCKS

Volvo Trucks' largest manufacturing facility in the world is in Dublin, Virginia. In 2012, it began a Supply Chain Optimization project with Genedge Alliance, the MEP in Virginia. The project began with a workshop at Volvo, covering multiple areas of SCO including TCO, constraints management, value stream mapping, supply chain strategy development, and other tools. This was followed by workshops and training with multiple Volvo suppliers. Now, Volvo has developed a dedicated staff to continue the work.

So far, Volvo Trucks has identified millions of dollars of savings in reduced waste due to better coordination. The main tool they have used has been Value Stream Mapping (VSM), a lean manufacturing tool used to document, analyze, and improve the flow of information or materials required to produce a product or service for a customer. VSM allows for the identification and visualization of wastes/losses and enables building a future state with those wastes/losses removed. Volvo has used VSM in its internal operations and has adapted the process to minimize unnecessary costs in its supply chain. Some examples include:

- Volvo learned that a major supplier did its production scheduling on Sunday evening. Volvo was sending them its orders on Monday, information that the supplier did not take into account until the following Sunday. Volvo moved to issue its orders on Sunday, a single action that reduced lead time by 5 days, allowing the supplier to fill rush orders that it could not fill before.
- A supplier consistently delivered several days early, requiring Volvo to find a place to store this inventory until it was needed. Volvo learned that the supplier thought that the due date on Volvo's instructions did not include transit time, which Volvo had in fact included. Once this miscommunication was cleared up, the supplier delivered consistently exactly when needed.
- Not everything works out. Volvo identified a situation in which a supplier was shipping entire cab hoods from several hundred miles away. The supplier molded three parts, and then bonded them together in its South Carolina facility, meaning that the supplier was shipping complete cab hoods and "millions of dollars' worth of air" to Volvo in Virginia, according to Mike Warfield, Volvo Truck Supply Chain Support Manager. Volvo asked the supplier to consider building a plant near Volvo's final assembly factory in Dublin to bond the parts so that they could be packed more tightly for shipping, thus requiring fewer shipments. However, based on Volvo's demand alone, the supplier did not have minimum efficient scale to make a nearby bonding operation profitable. Had there been other customers near to Volvo with the same need—a relevant industry cluster—the move could have worked.

Volvo Trucks has now done three iterations of Cost Deployment, a formal multi-step process used by world-class manufacturers to identify and quantify wastes/losses and implement improvement plans, identifying double-digit millions of dollars of savings each time. Even as Volvo fixes the problems identified, the potential savings continue to rise as Volvo becomes better at quantifying potential savings and seeing new opportunities for continuous improvement.

awarded competitively. When the grants expire, continuation of the services will be dependent on client companies' willingness to pay. This challenge may be somewhat more manageable with the recent change in MEP matching requirements. In 2016, Congress changed the required ratio of federal to non-federal funding from 1:2 to 1:1, which should provide greater flexibility for MEPs to reach more small manufacturing firms and to provide services to national supply chain networks.

Third, **because of history and the state government partners that co-fund MEPs, it is often difficult to pursue projects across state lines**. Most OEMs have suppliers that span multiple states. As several of the examples have noted, MEPs can develop mechanisms that allow each local MEP to provide consistent services throughout the supply chain, but they may not share the up-front costs of defining project scope, developing a training curriculum, or engaging in other essential marketing and communication activities. Consistent, fair mechanisms are needed to share costs and revenue across states to maximize the impact that MEP can have on national supply chains.

Finally, although MEP has worked with OEMs at various times, these projects have typically been focused in particular states where the OEM has a large manufacturing footprint. Working with large firms nationwide is difficult, given the program's focus on SMEs, but is essential for supply chain improvement. **OEMs and Tier 1-2 manufacturers have outsized influence on their suppliers' investment in technologies and capabilities. If MEP is to have the impact needed to transition more suppliers and end-to-end supply chains to the integrated, flexible, innovative future, MEP centers will need to work directly with OEMs and top tier manufacturers.** The Northeast Region Next Generation Supplier Initiative is focused on making this connection between OEMs and SMEs to create an effective model for nationwide use.

DEPARTMENT OF DEFENSE SUPPLIER SUPPORT

DoD plays an important role as a very large scale buyer from what has become a very large and diverse defense industrial base. As the buyer at the top of the supply chain for a wide range of weapons systems and other final products, the DoD can impose conditions on the supply chain, such as small business set-asides whereby a set proportion of an acquisition contract must be fulfilled by small business. These provisions have provided many small manufacturers with an initial start that has blossomed into more commercial production.

DoD also has specific programs to ensure that the domestic manufacturing base has the capability to produce critical components to avoid foreign dependencies that could increase risk to the supply chain in a crisis. In addition to small business set-asides in procurement contracts other specific programs have long supported small manufacturers. The Office of Manufacturing and Industrial Base Policy oversees multiple programs to support manufacturing, including DoD funding for six of the Manufacturing USA institutes and the Manufacturing Technology (ManTech) program which focuses on ensuring that the United States maintains critical production capabilities. The Office of Technology Evaluation has completed multiple industrial base assessments to determine the status of supply chains in carbon fiber composites, acoustic transducers, printed circuit boards, space industries, and other industries critical to defense capabilities.[46]

A few recent initiatives illustrate how DoD supports smaller suppliers and the overall defense supply chain:

- Defense Industrial Base Now (DIB-Now) is a data base of defense suppliers, available

[46]See https://www.bis.doc.gov/index.php/other-areas/office-of-technology-evaluation-ote/industrial-base-assessments.

to procurement officials and other defense contractors, that describes supplier capabilities, products, and services to fill the information gap facing buyers and sellers in the supply chain.

- QuickPay is an initiative launched in 2011 to accelerate payments to small companies within 15 days. The initiative was later extended to prime contractors, with the expectation that they would pay their small suppliers in 15 days. (QuickPay applies to all federal agencies, but as the largest federal customer, DoD's implementation of the policy has had the largest impact on manufacturing suppliers.)

- The Office of Economic Adjustment (OEA) works with suppliers and communities impacted by changes in defense procurement to adjust to the loss of defense business. For example, the Defense Manufacturing Assistance Program (DMAP) is an OEA-funded National Demonstration Program that is being conducted in Michigan, Ohio, and Indiana to diversify defense suppliers. A collaboration between the University of Michigan, Purdue University, and The Ohio State University, the program provides technical and business assistance to defense manufacturers and defense-dependent communities adversely affected by changes in defense procurement. DMAP started in June 2014 and is planned to continue through June 2018. It provides companies with an assessment and action plan for entering non-defense markets, then provides up to $100,000 to match company funds to implement projects in the action plan. To date DMAP has introduced 1214 companies to the program, 171 companies have begun the assessment process, 92 have been admitted to the program, and 84 client projects are complete or in progress. On the community side 177 communities have been introduced to the program, 92 are in the assessment stage, and 29 projects have been scoped, bid, or are in progress. Because the program is funded as a National Demonstration Program, special attention has been paid to ensuring that the functioning of the program yields a process that is replicable and scalable.

- Another OEA-funded program has worked with several MEP centers, including Washington and eastern Pennsylvania, to help small defense suppliers adjust to procurement changes. For instance, Impact Washington (MEP) and local economic development agencies in Seattle worked with six small companies to implement a Next Generation Lean program. The six companies, ranging in size from 45 to 600 employees, were able to reduce process times, reduce costs, increase revenue by as much as 40 percent, and increase weekly production by 87 percent.[47]

DEPARTMENT OF ENERGY ADVANCED MANUFACTURING OFFICE

The Advanced Manufacturing Office (AMO) serves as the focal point for multiple DoE programs that provide technical assistance to manufacturers. The AMO partners with large and small businesses, universities, and other stakeholders to invest in emerging clean energy technologies with the potential to create domestic manufacturing jobs and strengthen U.S. manufacturing competitiveness. Using public-private partnerships, the AMO supports R&D in advanced manufacturing processes and materials, and shares technical facilities at DoE laboratories to help transition

[47] See http://wamilitaryalliance.org/wp-content/uploads/2017/02/3B1_White-Paper_Case-Studies_Manufacturing-Pilot.pdf.

innovations into new manufacturing capabilities. Examples include:

- Next Generation Manufacturing Processes: Focused on four process areas—reactions and separations, high-temperature processing, waste heat minimization and recovery, and sustainable manufacturing—AMO funds specific projects with industry partners to advance the state of the art and commercialize the results.
- Next Generation Electric Machines is an R&D effort leveraging recent technology advancement in power electronics and electric motors to develop a new generation of medium voltage drive systems for a variety of applications. Participating companies include Eaton, General Electric, and Calnetix. The project will also leverage the work of Power America, one of the DoE-funded Manufacturing USA institutes.[48]
- The High-Performance Computing for Manufacturing Program (HPC4MFG), led by Lawrence Livermore National Laboratory, provides funding, expertise, and access to high-performance computing systems at national laboratories. Ten projects were announced in early 2016 with companies including United Technologies, PPG Industries, GlobalFoundries, General Electric, Shiloh Industries, Actasys, and ZoomEssence.[49]

SMALL BUSINESS ADMINISTRATION

The Small Business Administration has been supporting American small businesses since the early 1950s, providing access to loans, business advice, and a variety of other services to small businesses of all sorts, including manufacturers.

In recent years, several initiatives targeted directly at supply chains have been started, motivated by studies showing that small businesses that are part of large corporations' supply chains experience increased revenues and employment. Examples of specific SBA efforts in supply chains include:

AMERICAN SUPPLIER INITIATIVE

Announced in 2012 the American Supplier Initiative is a call-to-action to private-sector companies to invest in their supply chains' small businesses. The initiative aims to address four key areas in which small businesses need help in order to become successful suppliers in the private sector: access to mentorship and counseling services, increased market and revenue opportunities, ready sources of capital to fund their growth, and a highly skilled workforce.

SUPPLIER CONNECTION

Created by the IBM Foundation, Supplier Connection is a free, online portal that allows small businesses to send information about their products and services to 15 large private sector companies. The 15 companies participating in Supplier Connection are AMD, AT&T, Bank of America, Caterpillar, Citi Group, Dell, Facebook, IBM, JP Morgan Chase, John Deere, Kellogg's, Office Depot, Pfizer, UPS and Wells Fargo. Together, these 15 companies have a combined purchasing power of $300 billion and will now have full access to the profiles of small businesses that have registered for Supplier Connection.[50]

SUPPLIERPAY

The SupplierPay Initiative was launched in 2014 to partner with large companies to increase small suppliers access to working capital. Nearly 50 companies agreed to participate by working with suppliers to find financing solutions that can

[48] See https://energy.gov/articles/energy-department-awards-22-million-support-next-generation-electric-machines-manufacturing.
[49] For individual project descriptions, see https://hpc4mfg.llnl.gov/projects-spring2016.php.
[50] See https://www.sba.gov/about-sba/sba-newsroom/press-releases-media-advisories/sba-announces-new-partnership-connect-small-businesses-corporate-supply-chains.

lower their borrowing costs, to implement flexible payment terms, and to pay supplier invoices quickly. Coca-Cola, Honda, Toyota, and Intuit are a few of the companies actively participating in the SupplierPay Initiative.[51]

STATE PROGRAMS

States with large manufacturing sectors have long been proactive in providing resources and technical assistance to their manufacturing SMEs. Even before the MEP program, states such as Georgia, North Carolina, Ohio, Michigan, and Pennsylvania had programs to help manufacturers, often through university-based industrial extension programs. With the advent of MEP, nearly every state provides financial support to help meet the cost share requirements of MEP cooperative agreements. Several states have moved beyond the extension model to provide other types of services and support for smaller manufacturers.

Ohio, for example, has been aggressive in providing support for the state's manufacturers. To develop a strategy for future efforts, the Ohio Manufacturing Institute generated technology roadmaps for four manufacturing processes: molding, machining, joining and forming, and additive manufacturing. The roadmaps were developed with input from industry, academia, technical centers, MEPs, and government to help guide future resource allocation and areas of emphasis in state programs. Manufacturers identified four issues of greatest concern for the future of manufacturing supply chains in Ohio: 1) workforce, 2) advanced materials, 3) smart manufacturing, and 4) innovation and commercialization. To engage manufacturers and various service providers in addressing these concerns, the state has developed the Ohio Advance Manufacturing Technical Network. It provides a central repository of information on resources and expertise available to support Ohio manufacturers.

One such resource is **AweSim**, a partnership between the Ohio Supercomputer Center, simulation and engineering experts, and industry to provide manufacturing SMEs with access to high-performance computing-based modeling and simulation technology. AweSim emerged from the National Digital Engineering and Manufacturing Consortium (NDMEC), a public-private partnership started with $4.5 million from the federal Economic Development Administration, Purdue University, the Ohio Board of regents, and John Deere, Lockheed Martin, and Procter & Gamble. The NDMEC leveraged the resources of the Ohio Supercomputing Center and the expertise at Purdue University to provide manufacturing SMEs with sophisticated computer-aided design and engineering tools that greatly accelerate product and process design.

AweSim builds on the foundation created by NDMEC, building a cloud-based infrastructure to provide SMEs access to high-performance modeling and simulation tools using an app-based interface and a pay-as-you-go model. AweSim also provides educational materials, training, and access to industry-specific expertise and consultants to offer SMEs state-of-the-art modeling and simulation applications from their desktops. Currently 21 apps are available on the AweSim website for applications such as thermal analysis, air flow, drag and trim analysis, and data visualization.[52] To reach as many SMEs as possible, AweSim works with national manufacturing and engineering associations to provide links to the the AweSim platform through the associations' websites. The association gets a percentage of the revenue each time AweSim is accessed through its site, creating a revenue stream for the association and an effective mechanism for AweSim to reach a much larger audience.

[51] See https://www.sba.gov/content/supplierpay-case-studies.
[52] See https://www.awesim.org.

Based on this sample of the various state and federal programs, there seems to be no shortage of efforts to provide technical and educational assistance to manufacturing SMEs, to address problems with access to working capital, and to facilitate collaboration and communication to overcome network failures. Yet the trends in economic data and results from industry surveys fail to reveal strong movement toward the use of advanced manufacturing technologies or the various technologies needed for effective digital, flexible supply chains. Too many programs are disjointed, reflecting the uniquely American fear of industrial policy, yet with the right coordination, effective communication to the manufacturing community, and buy-in from the large firms that drive change in the supply chain, sufficient resources are likely available to achieve the next generation supply chain that is essential for long-term competitiveness. A common vision for the technologies and management practices embodied in future networked supply chain relationships will help to accelerate the transition.

THE NEXT GENERATION OF SUPPLY CHAIN INTEGRATION

Researchers and analysts are notorious for predicting future technologies, the "Factory of the Future," that rarely come to pass in the predicted timeframe. Many factors must come together for the vision of an integrated, knowledge-based optimized manufacturing ecosystem to be realized in the commercial market. Nevertheless, a predictable, recognizable set of technologies is emerging that could reshape manufacturing and require preparation and investment by both large and small companies. Forecasts include:

MODELING AND SIMULATION

Computer-aided modeling and simulation will move beyond early adopters to become standard practice across multiple industries and product types. In these industries, nearly all suppliers will be expected to have the capability to work from computer models that are imported directly to production equipment over the network. Of course, modeling software will become sufficiently precise and error-free to make this networked, model-based production commonplace. Resources such as AweSim and HPC4MFG will facilitate access to the high-performance computing needed to take full advantage of modeling and simulation.

ADVANCED MATERIALS

Continued development and use of advanced materials, such as composites, lightweight metal alloys, nanomaterials, and thin films, will have an impact on supply chains as the manufacturing processes needed to use these materials at a competitive price spread through the manufacturing ecosystem. In many cases, the new materials are still in development—their properties and potential applications are still being explored. Several Manufacturing USA institutes are working with advanced materials, including composites (IACMI), lightweight modern metals (LIFT), and functional fabrics (AFFOA), to accelerate development of cost-effective manufacturing processes and to disseminate these solutions to the broader commercial manufacturing community.

ADDITIVE MANUFACTURING

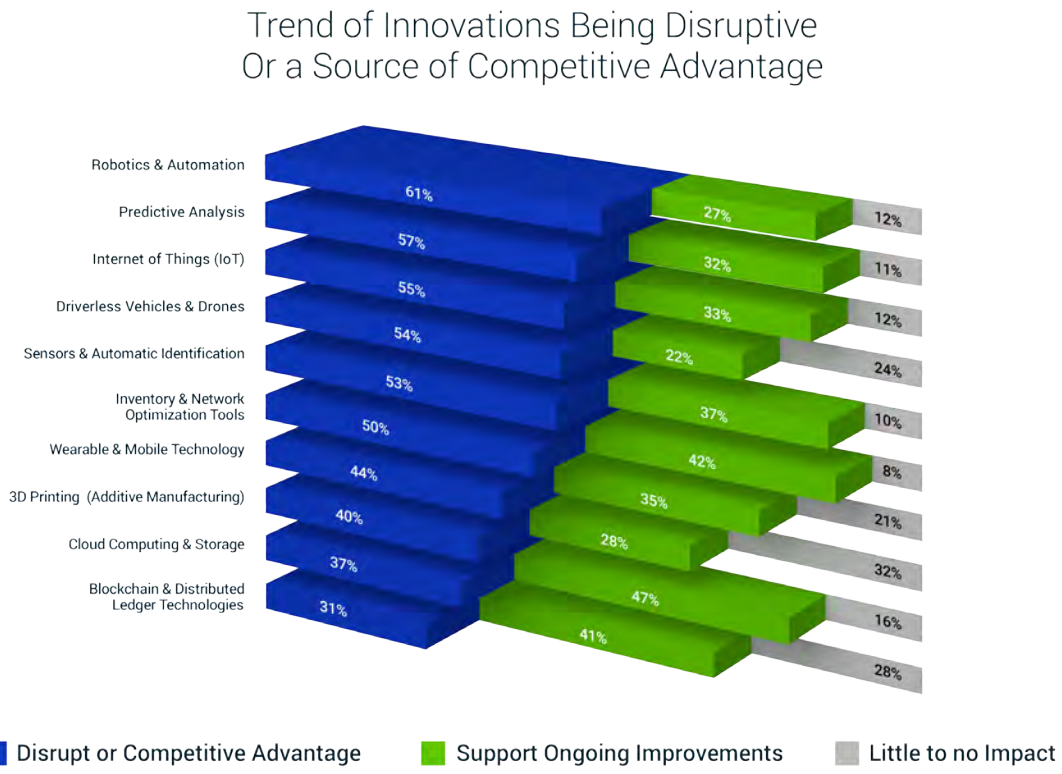
Colloquially known as 3-D printing, additive manufacturing will be applied to an increasing number of parts, creating complex parts from a variety of metallic and non-metallic materials

and typically reducing part counts in assemblies significantly. Already, two-thirds of surveyed manufacturers are using additive manufacturing in some way, and the global market is projected to be $6 billion in 2017.[53] As an example of the impact this technology can have, GE Additive is making a fuel nozzle for the LEAP engine using additive technology that reduced the part count from 20 to 1. Larger, more complex parts promise even larger reductions in part counts, a development that will have broad impacts on the number of needed suppliers.

ROBOTICS

Industrial robots could be on the verge of revolutionizing manufacturing. One recent industry survey identified robotics as the technology with the greatest potential to disrupt industry and create competitive advantage (see Figure 9).[55] They are becoming smarter, faster, more dexterous, and cheaper, with greater sensing, trainability, and ability to work cooperatively and safely with people. Use of robotics is likely to accelerate, limited more by the expertise and skills needed to exploit them than by technological barriers.[56] The Advanced Robotics Manufacturing (ARM) Institute in Pittsburgh, one of the Manufacturing USA institutes, is working to accelerate development and deployment of advanced robotics through collaborative R&D across multiple disciplines, including sensors, effectors, artificial intelligence, and behavior modeling.

FIGURE 9. DISRUPTIVE TECHNOLOGIES IN MANUFACTURING[54]



[53] PwC in conjunction with The Manufacturing Institute. *3D Printing and The New Shape of Industrial Manufacturing*. June 2014. http://www.pwc.com/us/en/industrial-products/assets/3d- printing-next_manufacturing-pwc.pdf.
[54] Deloitte and MHI, *Next Generation Supply Chains: Digital, On Demand and Always On*, 2017 MHI Annual Industry Report, p. 7, at https://www.mhi.org/publications/report.
[55] Ibid.
[56] PwC in conjunction with The Manufacturing Institute. *The New Hire: How A New Generation of Robots Is Transforming Manufacturing.* September 2014. https://www.pwc.com/us/en/industrial-products/assets/industrial-robot-trends-in- manufacturing-report.pdf.

ADVANCED PREDICTIVE ANALYTICS

Increasing sophistication and proliferation of information systems to capture and analyze data from multiple sources throughout the supply chain is providing greater operational insight for better management decisions. In one industry survey, more than one-half of respondents recognized the potential of analytics to create competitive advantage or to disrupt their industry, and nearly 90 percent expect to be using the technology within 6 years.[57] Arguably the consumer packaged goods industry is a first mover in data analytics with the best firms using point-of-sale data from retail outlets to track sales and the impact of pricing, promotions, and product mix; statistical data analysis and econometric models are used to track key performance indicators and to guide decision making.[58] Advanced analytics take many forms and are applied to data from multiple sources—sensors embedded in products, real-time data from production equipment, sales data, purchasing, etc. With effective information systems and analytical algorithms, companies can focus on maximizing customer value while minimizing inefficiencies throughout their supply chains.[59]

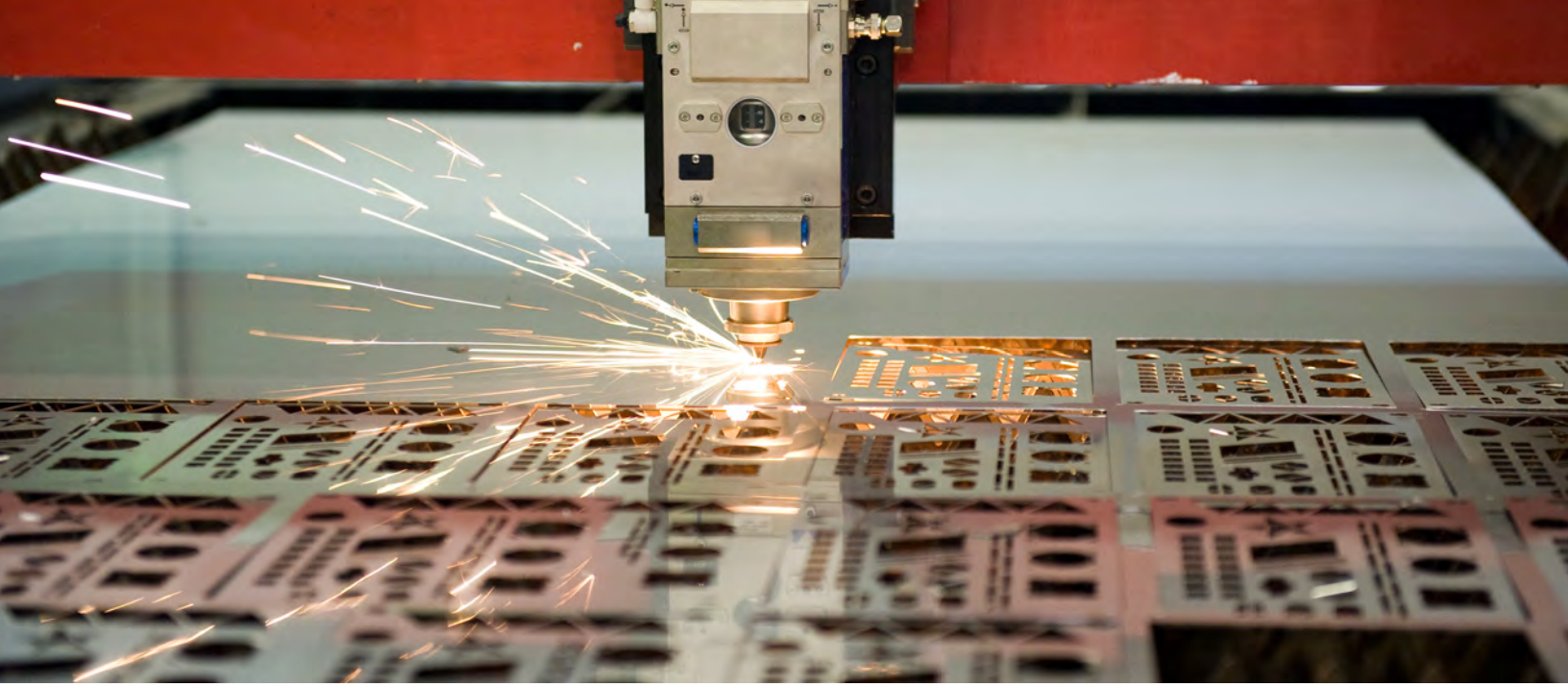
COLLABORATIVE AND DECENTRALIZED APPLICATION ARCHITECTURES AND DEVELOPMENT TOOLS

Customers, suppliers, and other stakeholders will collaborate extensively on common application platforms implemented through the cloud. Initial enabling technologies are already emerging, including new industrial operating systems, such as Predix from GE, that will take advantage of independent "app" developers; enterprise resource planning (ERP) systems that are integrated with suppliers; affordable, cloud-based ERP systems used by SMEs to integrate into larger systems from multiple customers; and integrated knowledge-based systems that support semi-automatic decision making. It is worth noting that these technologies will add another layer of complexity to the existing challenges of maintaining data security and integrity throughout the entire supply chain.

NETWORKED FACTORIES AND DYNAMIC SUPPLY CHAINS

Connectivity and mobility will be dominant themes in future manufacturing. Pervasive information systems, including sensors, industrial control systems, networks, and integrated planning, scheduling, and production systems will include OEMs, suppliers, distributors, and final customers. Eventually, autonomous systems will shift production resources dynamically, finding the best source for often customized parts while maximizing capacity utilization and overall efficiency of the entire production chain.

[57] Deloitte and MHI, *Next Generation Supply Chains: Digital, On Demand and Always On*, 2017 MHI Annual Industry Report, p. 7, at https://www.mhi.org/publications/report.
[58] Kari Alldredge, Jen Henry, Julie Lowrie, and Antonio Rocha, "Winning in Consumer Packaged Goods Through Data and Analytics," McKinsey & Co., August 2016.
[59] Stan Aronow, Mike Burkett, Jim Romano and Kimberly Nilles, "The 2016 Supply Chain Top 25: Lessons from Leaders," *Supply Chain Management Review*, Sept/Oct 2016, pp. 10-21.



GETTING FROM HERE TO THERE

Many of the technologies needed for the next generation of integrated, flexible, proactive, and optimized supply chains are already available. For many the lead industries are in consumer products. The data generated by both retail sales and electronic commerce have revolutionized the entire supply chain, driving agile production from global suppliers to real-time tracking of inventory of individual SKUs to specific data on purchasing patterns by location, time of year, and demographics. Many of the innovations made possible by the combination of big data availability and in-depth analysis are gradually penetrating other industries with a business-to-business sales focus. How fast this diffusion takes place is a subject of debate, though many in industry believe that the key technologies needed for digitally integrated supply chains will predominate within the next 5 years. For this to happen, several challenges must be overcome.

THE NEXT GENERATION SUPPLY CHAIN

Next-generation supply chain is common terminology in the management and technical literature. A consensus on their general characteristics include a combination of both new and old technology and management practices that together create vibrant, flexible, responsive supply chains to the benefit of all the OEMs and suppliers in the chain. Ideal characteristics include:

DATA DRIVEN: Increasing use of modeling and simulation, computer-aided design and engineering, sensors, digital control systems, multiple types of automation, and integrated information systems across supply chains create the potential to know more detail about both production processes and what is being produced. Information will be substituted for inventory, collaboration will be seamless, capacity will be balanced, and defects known and corrected immediately.

SUSTAINABLE: Some resources may become scarcer, demanding efficient use. The costs of environmental damage are likely to increase, prioritizing waste elimination. Clean energy will be preferred, and controls on emissions tightened.

FLEXIBLE: A combination of technologies and the continued spread of well-known lean production practices will allow next-generation supply chains to respond quickly to changing customer demand. Constant new product introductions and product differentiation will be cost effective and profitable.

GLOBAL—BUT ALSO LOCAL: Many products will continue to be designed, produced, and assembled in multiple countries for both global and local markets. For many other products, the need for rapid response to changing market demand, and the desire to minimize risk, will place new emphasis on proximity manufacturing, producing close to markets being served.

COLLABORATIVE: OEMs and suppliers will strengthen collaboration based on mutual interests to maximize value and meet customer demand. Those closest to production will work with designers who will work with customers to refine designs for performance, manufacturability, assembly, and sustainability. Collaborative problem-solving across functions and corporate boundaries will be common.

GOOD JOBS AND STABLE CAREER PATHS: Workers at all levels will contribute ideas, multitask, productively engage in problem solving, and constantly upgrade skills to adapt to changing technologies, product mix, and production processes.

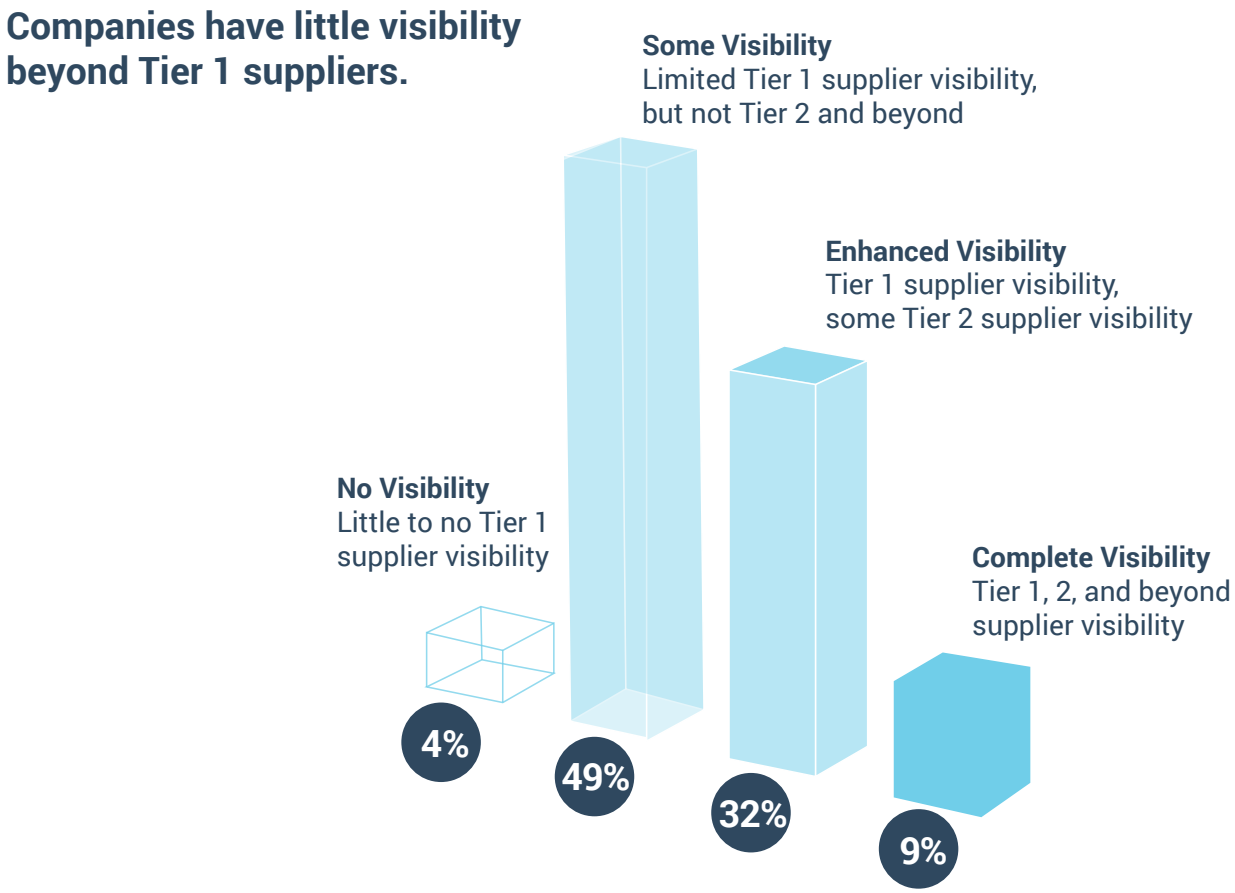
USE PROVEN TECHNIQUES, AS WELL AS NEW TECHNOLOGIES: Firms that automate processes successfully are usually those who understand well what the root causes of success and failure are in existing processes, and simplified as much as possible before automating. Lean production practices are likely to be essential to effective implementation of the many elements of next-generation supply chains.

Before making the necessary investment in new or upgraded capital equipment, information systems, and workforce development, manufacturers, especially SMEs, need a clear business case that gives them confidence that the costs will be justified by productivity improvements and new business opportunities, or at least business retention. These are the same reasons that suppliers have used to justify investments in lean production and quality systems. With appropriate information and mechanisms to make the needed investments more affordable, such as shared facilities, collaboration, and cloud-based SaaS, it is reasonable to expect managers to conclude that the costs, benefits, and risks work in their favor.

One barrier to investment in the digital supply chain is cybersecurity. **The more information systems are integrated throughout a supply chain, the more security risk flows from the weakest link in the supply chain.** Large companies may have the resources and personnel to manage cybersecurity risks, but smaller firms may not, thereby placing the whole supply chain at risk. Recent incidents have shined a spotlight on cybersecurity. Government, universities, and the private sector are devoting efforts to sharing information, identifying best practices to increase cybersecurity, and limiting vulnerabilities. It is unlikely that cybersecurity concerns will impede the emergence of digitally integrated supply chains, but steps will be needed to raise confidence that the threat is manageable. A forthcoming MForesight report will identify critical needs in research, business practices, regulations, and policy to address cybersecurity comprehensively and cement confidence in the digital manufacturing future.

Workforce issues are frequently cited by industry as a hindrance to adopting new digital technologies, whether in the form of ERP systems, modeling and simulation tools, or advanced industrial control systems. Most industry surveys cite hiring and retaining a skilled workforce as the

FIGURE 10. SUPPLY CHAIN VISIBILITY[60]



biggest obstacle to implementing more digital manufacturing technologies. Universities and community colleges around the country have been responding to these concerns, including instances in which companies work directly with a local educational institution to provide customized training and skill certifications. More of these arrangements will be needed to increase the supply of skilled workers, but in the meantime, creative ways to utilize the available workforce may be needed. **Job sharing across companies should be explored, or large firms could assign their employees to work at smaller suppliers.** Alternatively, the local MEP could provide the needed expertise, for instance to maintain or troubleshoot an ERP system. Firms and their customers may find that they need to pay more to attract new workers into these fields and to retain those they have already trained.

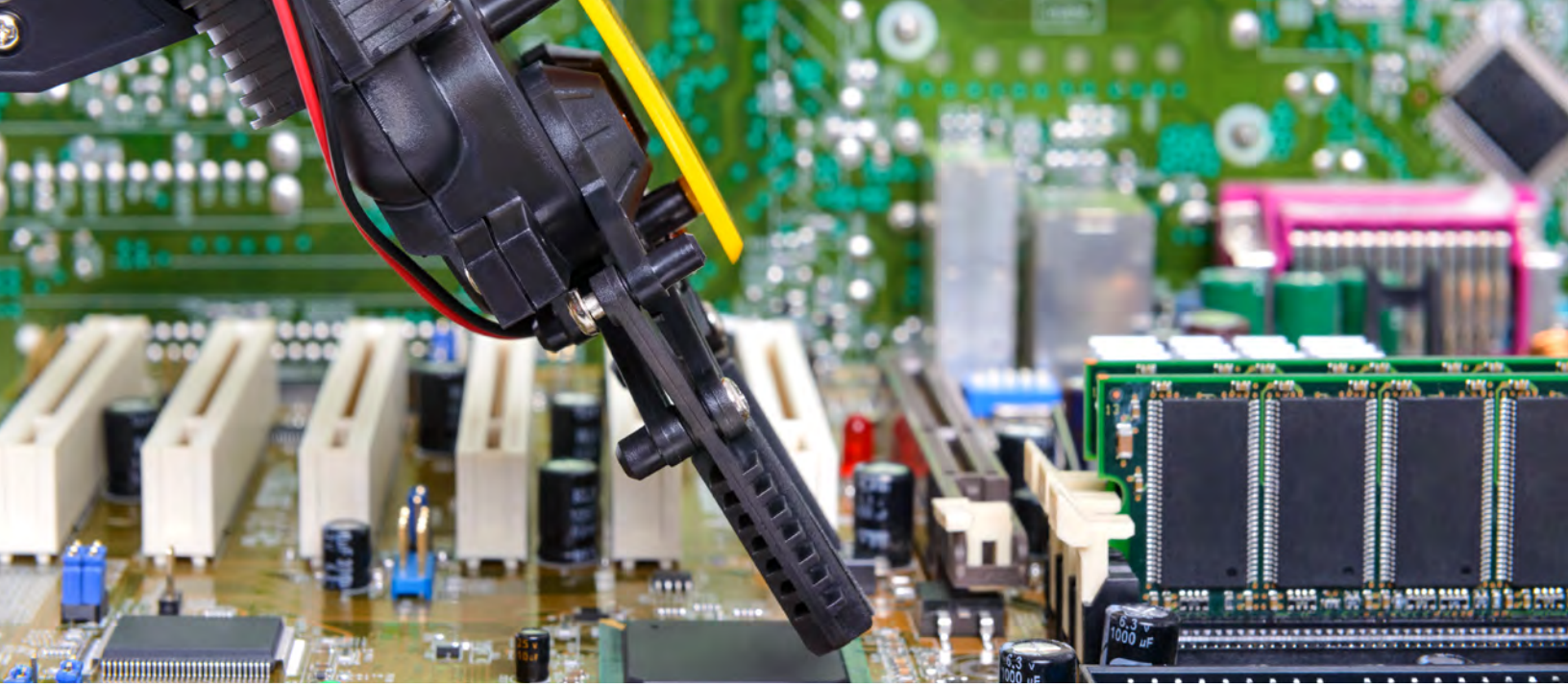
Ensuring that the nation's manufacturing ecosystems possess the necessary talent pool should be considered a priority. Just as identifying and providing access to product and process innovation is an integral part of developing and maintaining the health and competitiveness of the nation's supply chains, so too is identifying and developing innovative practices in workforce development.[61] Manufacturing is increasingly a multi-skilled, challenging work environment in

[60] Economist Intelligence Unit survey, Nov. 2012.
[61] MForesight is completing a report on game changing practices in education and skills development that will address many of these issues.

which frontline workers are expected to contribute to both production and innovation, working with existing and emerging technologies. The current education system has an inherent lag between demand created by innovation in manufacturing and changes in curricula required to meet that demand. Efforts to address this lag should include attention to multiple levels of education, not just degreed engineers, at the Manufacturing USA institutes and similar industry-focused technology development organizations.

Visibility throughout the supply chain is a frequent aspiration cited by larger firms, but few companies have much beyond the second or third tier (see Figure 10). ERP and related information systems promise to provide much greater visibility; "control towers" will provide the desired visibility, if the lower tier suppliers use compatible software. For a growing number of supply chains, having that compatible software may become a precondition to participating in a given supply chain. SMEs will need affordable access to compatible software, which several companies now offer. Other industries could emulate the aerospace industry's creation of Exostar to enable web-based sharing of information from different ERP systems. Smaller firms will also need coaching in how to implement an ERP system so that it benefits the SME and is not a burden that diverts resources just to manage the system. Finally, SMEs will need to be confident that they have some control of the information that their large customers can see. Visibility is viewed as essential to the OEMs, but their smaller suppliers may be hesitant to share detailed information with their customers.

Fortunately, resources are already available to address these barriers. The Manufacturing USA institutes and the MEP system, both driven and supported by the manufacturing community, have the needed expertise, are developing advanced technologies, facilitate collaboration and shared learning, provide training and coaching, and are positioned well to apply systems engineering methodologies to the total manufacturing ecosystem in a way that individual companies cannot. **These are national assets that should be appreciated and leveraged to address current gaps, to disseminate best practices, and to compete with advances in other nations.** Other resources, such as AweSim and HPC4MFG, should be evaluated, tweaked if necessary, and replicated to provide widespread access to advanced modeling and simulation and other technologies that can benefit from shared access to high-performance computing. As public-private partnerships, these programs are well-placed to understand the needs of industry, though a fee-for-service model can limit the ability to provide multi-company services or cutting-edge services that companies are not quite ready to buy. Continued public support will be essential lest familiar market and network failures overwhelm progress.



NEXT STEPS

Achieving the next-generation supply chain, with all the promise of flexible, customized, responsive production, is a complex proposition, requiring all the players in the manufacturing ecosystem to play a role. Obviously, business will take the lead, implementing tools and systems that provide competitive advantage, but government and educational institutions have important contributions to make, both as suppliers in their own right, and as facilitators, collaborators, and researchers. In fact, these sectors play integral roles in the manufacturing ecosystem. For the United States to maintain its leadership in innovation, the collective strengths of the full ecosystem must be leveraged.

COMPANIES

Companies should start by developing a strategy. **Although 90 percent of large manufacturers recognize the importance of their supply chains to business success—after all, 50-70 percent of their costs are in the supply chain—very few have a supply chain strategy.**[62] Those that do have been shown to be more profitable. Without a solid strategy and vision of what the supply network should be, implementing ERP systems and demanding suppliers do too is an expensive and likely counterproductive exercise.

With a solid strategy in place, companies should begin applying the best practices known to work for leading companies, starting with Total Cost of Ownership (TCO). MEP provides access to a TCO calculator and others are readily available. It is common for companies to find that the TCO of parts purchased domestically are within 15 percent of Asian suppliers, and sometimes even cheaper. Greater understanding of TCO, a focus of MEP's SCO services, could accelerate efforts to return manufacturing from Asia.

Using TCO would have the ancillary benefit of providing the basis for supplier performance metrics that go beyond cost, delivery time, and minimum quality levels. Although those factors will always remain preeminent, particularly for lower value purchases represented in the lower two quadrants of Figure 6, additional metrics reflecting supplier flexibility, engineering capability, process sophistication, use of modeling and simulation tools, ability to work with advanced materials, inventiveness, and overall collaboration could be factors that grow in importance.

TCO can also be the basis for improving trust throughout the supply chain because capabilities are better known and sharing information becomes integral to relationships. This can facilitate integration of ERP systems, generate data to reveal analytical insights, identify sources of value that benefit both buyer and supplier, and generally drive proactive management to achieve success of the total manufacturing ecosystem.

Although much of the improvement in a supply chain is driven by pull from the top, smaller suppliers also need to initiate performance improvements. Studies have shown that SMEs that are part of supply chains, rather than just order fillers, are more profitable and able to invest in new technologies. Resources such as MEP help SMEs improve their overall business management and increase the value of their production. They can collaborate with peers in Continuous Improvement User Groups;[63] proactively seek information on appropriate technologies to understand the business case for 3D modeling, ERP systems, additive manufacturing, and other technologies that can make their company more attractive as a supplier; and work with local educational institutions to define skill requirements for the present and future. Many improvement initiatives cost little; getting started is essential to avoid becoming irrelevant.

GOVERNMENT

If the generally accepted role of government in the United States is to address market and network failures and support national security, then existing programs, especially the Manufacturing USA institutes and MEP, are essential and effective. Public-private organizational models leverage the collective strengths and assets of both sectors to make advances that would otherwise be unattainable to many manufacturers. The Manufacturing USA institutes provide laboratories, shared production

[62] McKinsey & Co., *Excellence in Supply Chain Management,* Operations Practice, June 2014.
[63] Continuous Improvement User Groups are facilitated groups of local manufacturers, often from different industries, that work together to critique each other's facilities, identify improvement opportunities, and share best practices.

facilities, and forums for collaboration between researchers, government agencies, and both large and small companies. Their cooperation with MEP to embed staff at the institutes and to use MEP to diffuse new technologies created at the institutes expands their reach beyond member companies and increases the likelihood of significant long-term impact.

The MEP program has become an indispensable part of the total U.S. manufacturing ecosystem, and should be funded accordingly. No private, purely profit-dependent companies could successfully fill the position held by MEP. Smaller firms cannot pay significant consulting fees, private consultants cannot afford the time to market to SMEs, large customers typically provide little assistance, and universities have few available resources and high fees. Federal and state government support for MEPs allows them to retain expertise in engineering, marketing, information systems, and other fields critical to the success of small manufacturers, while affording the constant outreach necessary to gain new clients. MEPs are judged on the number and impact of fee-for-service projects they do, but those fees must be reasonable for small companies to buy the service. **Government funds are essential to make the model work for the target audience, SMEs.**

However, the challenge of improving supply chains introduces wrinkles in the MEP model that could be improved. For instance, supply chains typically span multiple states, but MEP centers are funded state by state and jealously guard reporting of projects in their state. Sharing of credit for reporting purposes can sometimes be worked out case-by-case, but a mechanism to adjust reporting guidelines to facilitate multi-state projects would be beneficial.

Similarly, it is important to remember that MEP centers are mandated to work with SMEs, defined as firms with fewer than 500 employees. OEMs and Tier 1 suppliers are typically much larger. Although MEP has worked with these large firms in the past, mainly to identify their suppliers and to help the suppliers meet lean production and quality objectives set by the OEM, more in-depth work with OEMs would be very beneficial to MEP's efforts in supply chains. Working collaboratively across multiple OEMs, as the MEP pilot initiative in the Northeast Region is doing, to facilitate supplier performance upgrades adds even more value and helps to avoid free rider concerns. **With their unrivaled knowledge of suppliers, MEP could work with OEMs to develop holistic supply chain strategies to capture the value suppliers offer.** Having "permission" to work with OEMs in the context of supply chains would leverage MEP's existing efforts in SCO to the benefit of large and small manufacturers.

MEP might also play a larger role in improving SMEs' access to the technical expertise needed to participate in digitally integrated supply chains. For instance, an MEP could hire and train experts in the ERP systems appropriate for SMEs. The MEP expert could help set up the system, train SME staff in data collection and entry, and perform maintenance functions periodically for multiple SMEs so they could avoid hiring information technology experts. A similar function could be played with simulation and modeling software, in which the MEP provides an expert to deal with 3D models as the need arises at the supplier. The MEP staff could also play an important role in facilitating SMEs' use of AweSim and other cloud-based modeling and simulation computing environments as they emerge. Part of this effort could be to encourage local engineering students to work with SMEs on computer-aided design and engineering, which would provide an introduction to this technology that a majority of SMEs still do not use.

Other agencies or state governments could take steps to improve SMEs' access to the technology that is integral to digital supply chains. For instance, **the Small Business Administration**

could create a loan fund specifically targeted at smaller manufacturers to upgrade their production equipment, networks, sensors, and information systems. Shared facilities, such as AweSim in Ohio and the HPC4MFG program and national labs, could be replicated, particularly in modeling, simulation, and virtual reality where internet access to the required high-performance computing avoids the need for a physical presence.

Given the 58 federal government programs available to help manufacturers (according to the GAO), plus multiple state programs, compiling and making information easily available to the manufacturing community would increase efficiency and effectiveness. Greater coordination between the various programs would also facilitate joint problem solving of common issues and minimize confusion in the target audience, especially small and medium-sized manufacturers.

EDUCATION AND TRAINING

It is important to remember that **educational institutions of all sorts—universities, community colleges, vocational schools, and high schools—are also suppliers to manufacturers.** Other organizations, including MEPs, unions, professional societies, and trade associations, provide training on a myriad of topics, from skilled trades to lean production principles and quality system implementation to cost accounting, bidding, marketing, and general management. These institutions and organizations are critical players in the total manufacturing ecosystem, and what they supply—skilled individuals—is the single most important ingredient in a healthy ecosystem that can adapt, innovate, and compete successfully.

Finding manufacturing skills, in existing production environments and the next-generation supply chains beginning to emerge, is frequently cited by manufacturers as their biggest challenge. In many cases, the perceived shortage is due to a company's unwillingness to pay wages sufficient to attract or retain needed talent,[64] which can lead to positions left vacant or poaching. **Too frequently, larger companies that can afford to pay higher wages poach skilled employees from suppliers, leaving the smaller companies with the burden and cost of training new employees.** This pattern is visible among tool and die makers in the automotive industry. Greater than 70 percent of tool and die makers working at automotive OEMs are at or near retirement age, but OEMs brought on new apprentices only in 2015. To compound the problem, many OEMs design new tooling domestically, have it built offshore, then test and modify it back in the United States. This process may be cost effective in the short run, but leaves unanswered the question of how workers can make effective changes to a die if they have never built one.[65]

The emergence of advanced manufacturing technologies and the digital technologies that enable next-generation supply chains introduces additional complexities into an already complex environment for manufacturing skills. Too often, broad market penetration of new technologies is inhibited by the availability of workers who can operate them. Expecting young people to train for specific technologies that are not widespread in the market may be unrealistic, though the Manufacturing USA program can certainly help train the first wave of operators and implementers. More realistically, **the Manufacturing USA institutes, MEP centers, and others can help define a broad set of skills that will prepare new manufacturing workers to adapt to new**

[64] Cappelli, Peter H. "Skill Gaps, Skill Shortages, and Skill Mismatches: Evidence and Arguments for the United States," *ILR Review* (2015): 0019793914564961.
[65] Kristin Dziczek, "Apprenticeship in Automotive Tool and Die", Center for Automotive Research, May 2017.

technologies quickly, develop specific curricula for these skill sets, and help to disseminate these curricula to educational institutions. With input from multiple players, this process will help the workforce get ahead of the curve, training for tomorrow's careers rather than yesterday's.

Apprenticeship is a proven method of training a workforce that has both the applied knowledge needed to use existing technologies, and also the understanding of fundamental principles that will help them and their employers apply and shape the technologies of the future. **Apprentice programs are beginning to increase in multiple skilled trades, encouraged by the U.S. Department of Labor, unions, and other organizations, but the number and breadth of apprenticeships remains a fraction of those available in other countries such as Germany.** Some companies, even SMEs, incentivize employees to upgrade their skills. Oberg Industries, a precision manufacturer in Freeport, Pennsylvania, pays tuition expenses, provides time from work, and increases the wages of employees who upgrade their skills; the company also has an extensive apprentice training program.[66]

RESEARCH

Managing supply chains can be a source of strength—or weakness—for both firms and communities. Several technologies and tools have been described that will create the next generation of supply chains. Yet a variety of questions remain, which are topics for future research.

CAPABILITY OF SUPPLY CHAIN FIRMS AND OTHER INSTITUTIONS

Supply chain capability is a function of a) the capability of the firms and other institutions—universities, governments, unions, other intermediaries—that comprise them, and b) the quality of the interfaces among these entities.

Public support for economic growth has long focused on the diffusion of physical technologies, yet the diffusion of operational insights may be just as valuable.

When suppliers are not capable of adopting the latest technology, delivering on time with high-quality, low-cost products, the entire supply chain suffers. For example, if lower-tier suppliers cannot read 3D models, then the complexity of products that lead firms can offer may be limited. If suppliers cannot change molds and dies quickly, or ramp up efficiently to make new products, then the ability of both lead firms and start-ups without manufacturing capability to experiment with new designs may also be limited. This interdependence raises several research questions:

- How do supplier firms learn about new technologies, materials, and management practices, and how do they decide which ones to adopt?
- What practices can speed the diffusion of useful technologies?
- How do they obtain financing?

Institutions such as universities, unions, and intermediaries can develop and spread best practices in technology and management. The benefits of these institutions spill over even to those who do not pay for them. Thus, they suffer from a variety of network and market failures.

- How can effective intermediaries be created and maintained? Who should pay for them? Who should have influence on their governance?

QUALITY OF INTERFACES AMONG FIRMS AND OTHER INSTITUTIONS IN SUPPLY CHAINS

The innovativeness of supply chains also depends on the ability and incentives of their

[66] See http://www.esa.doc.gov/reports/benefits-and-costs-apprenticeships-business-perspective.

members to obtain and share information. In a market that already has many buyers and suppliers for an existing product, not much information other than price information needs to cross firm boundaries; products and prices can be advertised online, and buyers do not need to know how something was made to determine whether it works. In today's supply chains, however, new products and processes are being developed constantly, and thick markets may not exist. A great deal of improvement in price and performance can be obtained if suppliers and customers communicate about what processes they are using, where inventory is located, what vulnerabilities exist, etc. An exploding variety of technical tools makes the potential for connected supply chains much greater than in the past. However, integrated changes in management and technology are needed to achieve the vision of seamlessly connected firms, equipment, and processes embodied in ideas such as Industry 4.0. Adopting these tools poses a number of challenges, about which more research is needed:

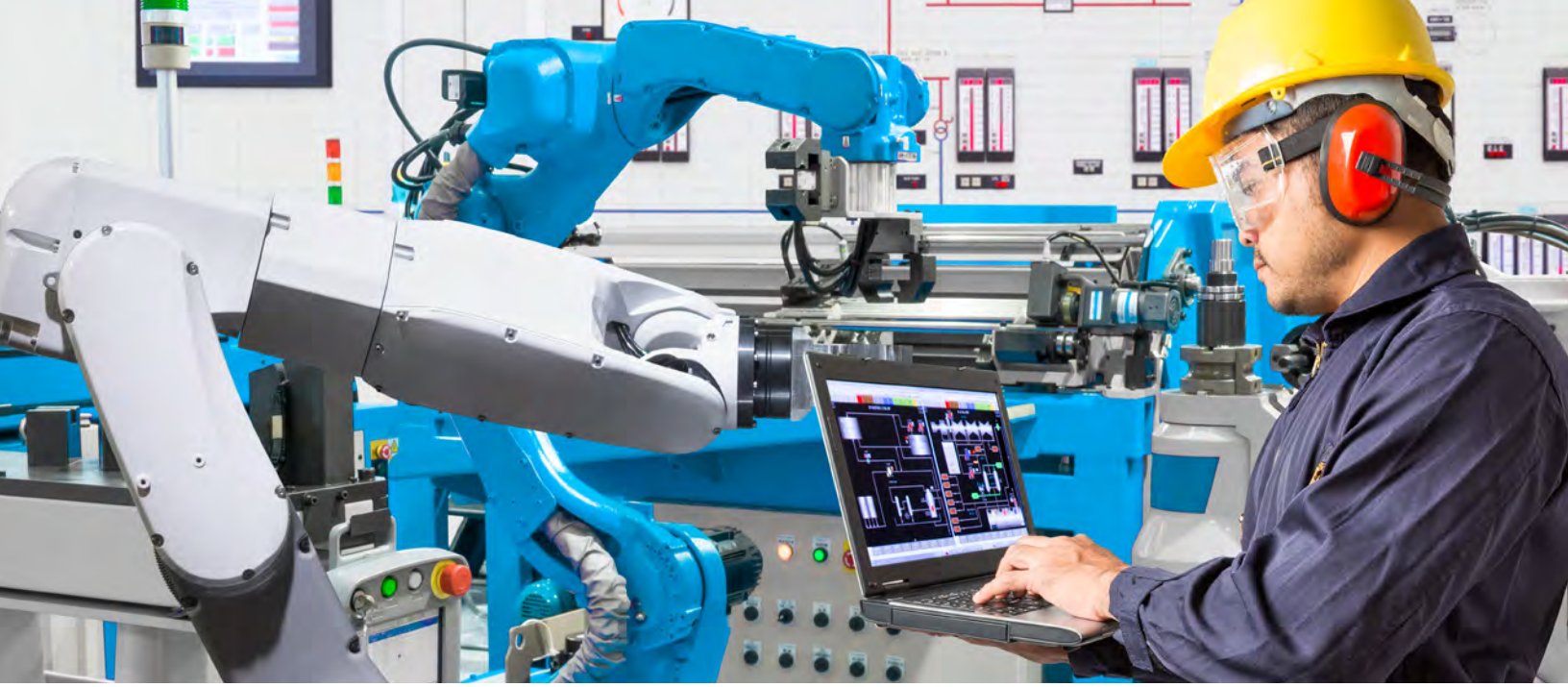
Data availability and access

- How do firms *obtain the data* needed for sophisticated algorithms to work? How can firms incentivize lower-tier suppliers to provide the information needed on issues such as their inventory, capacity utilization, costs of process steps, etc.?
- Once data is obtained, *what new algorithms can be developed to improve decision-making*, for example, decisions about trade-offs in choosing suppliers? What is the value of reduced lead time, increased quality, etc.? Sophisticated tools allow firms to move beyond making decisions using point estimates to instead consider the value of reduced variance of outcomes. For example, an offshore supplier may have a lower price if all goes well, but the larger number of possible adverse events may make the risk of using such a supplier greater. How much is it worth to reduce such risks?
- What standards are needed to enable equipment used by supply chain participants to connect to information networks? Proprietary standards may enable a more seamless connection, but they also create the possibility of monopoly power.
- Who should have access to data generated by systems such as Industry 4.0? Some envision a lead firm being able to control every piece of equipment in its supply chain regardless of the supplier's location. Another possibility is a virtual "walled garden" that limits access to certain groups for certain types of data. A third is widely decentralized data, including for shop floor workers to understand how their decisions affect and are affected by decisions made elsewhere in the chain, allowing contextual knowledge to flow up (as well as commands to flow down). What are the benefits and costs, and implications for income distribution and future innovation, of these various types of arrangements?

Nurturing vibrant ecosystems

- Despite the availability of sophisticated data and algorithms, many firms are still organized into silos, in which each silo optimizes its own outcomes, even at the expense of benefits to the firm as a whole. How can these silos be overcome without generating a confusing amount of complexity? Lessons can be learned from companies that have already eliminated silos.
- How can firms *generate the right incentives for collaboration* within and between organizations? Often, deep collaboration requires investments in specialized knowledge or equipment, or trusting that a partner will not use information provided to reduce a supplier's profit margin. What is the right amount and nature of commitment that a firm should provide, to gain the benefits of collaboration without being excessively locked in?

- Investments made in a supply chain are currently difficult for outside investors to value. What kinds of steps or tools would help Wall Street and other investors measure the value of such investments that a firm captures privately?
- Effective supply chains have benefits that spill over to communities, workers, and other firms. How can the size of these spillovers be measured? What public policies are effective in generating such spillovers?



CONCLUSION

U.S. manufacturing has evolved tremendously in the past few decades. Foreign competition, especially from Japan beginning in the 1980s, drove a focus on quality, followed by a shift in strategy to emphasize core competences, and then the spread of lean manufacturing principles. A focus on lowering costs drove manufacturers to low-wage countries and fostered the growth of sophisticated production capabilities in Asia. As these trends grew across multiple industries, suppliers became both more important to overall competitiveness and faced ever-increasing performance demands on cost, quality, and delivery. Suppliers now account for 50-70 percent of a typical manufacturer's final production value. Optimizing this supply network has become essential to effective, competitive manufacturing in virtually every industry.

As manufacturers have recognized the importance of their value chains, leading firms have begun to move beyond arm's length relationships with suppliers that assumed quality certifications would guarantee high-quality outcomes. These firms realize that their suppliers can be a source of value enhancement and competitive advantage, and have built partnerships to interact with suppliers on product design, engineering, capacity management, and, at least sometimes, training and technology enhancements.

The next generation of supply chain interactions recognizes the importance of the total manufacturing ecosystem. The emergence of advanced materials and production processes, robotics, sensors and digital control systems, and cloud-based ERP and supply chain management systems are enabling new capabilities. This next-generation supply chain creates opportunities for new, better, customized products delivered on demand with higher value and higher customer satisfaction. The needed technology is mostly already available but widespread adoption still requires encouragement, education, and commitment.

Private companies are unlikely to make the required investments fast enough, because of the many market and network failures that beset supply chains, especially the SMEs at the lower tiers. Both state and federal governments have long played a role to overcome these failures; programs are already in place to continue and strengthen this role. The MEP, Manufacturing USA institutes, and many other government programs and public-private partnerships could provide essential services to SMEs to hasten the transition to next-generation supply chains.

The opportunities are too great to ignore. U.S. competitors are not standing still. They are making concerted efforts to develop and apply digital manufacturing technologies. The challenges are many, requiring initiatives from companies, researchers, educators, and government. With effective action, this latest evolution in manufacturing can be a source of long-term competitive strength for U.S. manufacturing.

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