Strengthening the Innovation Ecosystem for Advanced Manufacturing

PATHWAYS & OPPORTUNITIES for MASSACHUSETTS

MIT Industrial Performance Center
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Strengthening the Innovation Ecosystem for Advanced Manufacturing: Pathways and Opportunities for Massachusetts

MIT Industrial Performance Center

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1 Executive Summary

Recent years have brought a renewed focus on the importance of manufacturing to the health and future growth of the U.S. economy. Specifically, several studies have highlighted the need to maintain and build manufacturing capabilities to support economic growth, good jobs, and national security. Most critically perhaps, they have **linked America's strength in manufacturing to its ability to innovate**. Advanced manufacturing capabilities are essential to develop new products and processes across a range of industries, both established and emerging. As others have pointed out, the loss of this capability can shift an industry's center of gravity as higher value-added activities follow manufacturing abroad.

In few states is the link between manufacturing and innovation more evident than in Massachusetts. While manufacturing represents only 9 percent of employment (approximately 250,000 jobs) in the Commonwealth (compared to 11 percent in the country overall), manufacturing is integral to several of the **state's most important industry clusters,** including aerospace/defense, semiconductors and computers, biopharmaceuticals, and medical devices. Massachusetts-based manufacturers compete globally on their innovation capacity, high skills, product quality, and rapid response.

A 2013 MIT study titled *Production in the Innovation Economy* highlighted the fact that the large, vertically-integrated corporations of the 1980s have become less vertically integrated over time as they have focused on their core competencies, outsourced much of their production, and increasingly relied on suppliers to drive innovation. This process has left **"holes" in the industrial ecosystem**, reducing many of the important investments and spillovers—in areas such as training, technology adoption, and R&D—that used to flow from large corporations to smaller firms. As a result, the country's small and medium-sized manufacturers often find themselves **"home alone"** when it comes to competing globally and driving innovation in their companies.

This report focuses on how to fill these holes as they relate to innovation. Our analysis uses **a systems approach** that considers how knowledge and sources of innovation flow between key participants within the manufacturing innovation ecosystem. Strengthening these links and expanding the flow of knowledge between key actors will upgrade the system as a whole and enhance the region's competitiveness. As other regions and countries around the world increase investment in manufacturing and incentives for manufacturing firms, it is increasingly important for Massachusetts to invest in and leverage its own innovation assets to fully establish itself **as a world-class leader** in advanced manufacturing.

Study Objectives and Research Methodology

The objective of this research is to find pathways and opportunities for building and fostering innovation capacity among Massachusetts manufacturers, with a particular focus on small and medium-sized enterprises (SMEs). Strengthening the regional innovation ecosystem as a whole will improve the **"industrial commons"** and help all manufacturers in the state, not just a select few.

To that end, we have sought to develop a deep understanding of the current manufacturing landscape and of the intermediary systems that support manufacturing in Massachusetts. Our research included a quantitative analysis of the state's industrial base as well as qualitative observations based on interviews with relevant actors in the innovation ecosystem. For benchmarking purposes we also included findings from interviews conducted in Germany.

Key Findings

1. Manufacturing in the Commonwealth Competes on Talent, Quality, and Innovation

Massachusetts has a long and illustrious history in manufacturing and in product and process innovation, and has built **advanced manufacturing capabilities** over the past 150 years that have allowed companies and workers to transition into new or emerging industries as market conditions change. In fact, one of the region's strengths is a diverse manufacturing base that supports **cross-fertilization** between key industry clusters.

Several **attributes** characterize manufacturing in Massachusetts:

- Small-batch, niche production rather than large-volume mass production;
- Extremely high quality and performance requirements (zero percent failure);
- High knowledge and innovation content;
- New or early-stage products and prototyping;
- Products with high proprietary content;
- Products where proximity to market is desirable;
- Products where regulatory factors encourage siting in the U.S.; and
- Customized products with quick turnaround time if needed.

These attributes are possible because large manufacturing companies can draw on **four primary assets**:

1. A well-educated and **highly skilled labor force**, particularly in engineering;
2. Suppliers with the ability to quickly deliver difficult-to-manufacture parts of very **high quality and reliability**;
3. **World-class universities**; and
4. Innovative startups and a dynamic **entrepreneurial ecosystem**.

For all of these reasons, Massachusetts continues to have a strong manufacturing base. Moreover, that base has stabilized since the 2008 financial crisis. As a result, manufacturers in the Commonwealth are well positioned to take advantage of recent national and global trends that suggest the U.S. may be more globally competitive in manufacturing in the future. Declining energy costs, rising labor costs in traditionally low-wage countries, and concerns about the protection of intellectual property are making the **U.S. a more competitive location** for certain types of manufacturing, including in particular those types of manufacturing in which Massachusetts excels. At the same time, the development of **new "game-changing" advanced manufacturing technologies,** such as additive manufacturing, cyber-physical systems, and integrated circuit photonics, is providing additional opportunities for U.S. firms to innovate and increase efficiency.

2. Advanced Manufacturing Capabilities Support a Diverse Set of Regionally Important Industry Clusters

Manufacturing employment in Massachusetts has steadily declined over the past several decades, dropping from 19% of total employment in 1990 to approximately 9% at present, in part due to the recessions of 2000 and 2008, as well as productivity gains. Today, employment has stabilized since the financial crisis to approximately 250,000 workers and 7,000 establishments in manufacturing. Approximately 97% of all manufacturing establishments in Massachusetts can be considered SMEs (with fewer than 500 employees) and about 92% have even fewer than 100 employees. Although SMEs vastly outnumber large firms, they generate a smaller fraction—only 30%—of all manufacturing jobs. Large firms—though they account for only about 3% of all manufacturing establishments in Massachusetts—employ approximately 70% of the state's manufacturing workers.

Massachusetts has a diverse set of strong manufacturing sub-industries that support some of the state's leading industry clusters. These sub-industries create foundational **cross-cutting capabilities** within the regional economy; ten of them are considered in this study because they are especially relevant for advanced manufacturing:

- Analytical Laboratory Instruments
- Search, Detection, and Navigation Instruments
- Industrial Process Variable Measuring Instruments
- Semiconductor Machinery
- Semiconductors and Related Devices
- Electronic Computers
- Aircraft Engines
- Surgical and Medical Instruments
- Pharmaceutical Preparation
- Machine Shops

3. The Massachusetts Manufacturing Innovation Ecosystem is Rich in Terms of Assets, but Relatively Poor in Terms of Interconnectedness

While firm innovation might have occurred in isolation in the past, particularly when many firms were vertically integrated, today's firms must have high degrees of interaction with a range of other companies and organizations, such as universities, suppliers, customers, and even competitors, in order to build a firm's innovation capacity.

Four key nodes and actors shape the advanced manufacturing innovation ecosystem in the Commonwealth:

- Large original equipment manufacturers (OEMs)—firms with more than 500 employees that manufacture marketable products based on 'original' designs,
- Supplier SMEs—firms with fewer than 500 employees that manufacture parts and components for OEMs,
- Startups, and
- Universities and research institutions.

While each node within the system is relatively robust, the strength of connection between them varies in terms of knowledge flows. In general, **OEMs** have the **strongest links** within the innovation ecosystem because they are driving much of the innovation. Knowledge flows between OEMs and research universities are strong in both directions, while knowledge flows with SMEs are relatively unidirectional flowing from OEMs to the SME. With respect to innovation, startups typically bring new ideas to the OEMs.

Over the past five to ten years, many OEMs have undergone a significant reorganization and rethinking of their supply chains. Pressures, primarily financial from customers, have forced them to rethink how best to drive greater efficiency and innovation from the supply chain. This has led to several major changes:

- **Integration of supply chain management with engineering** to bring design and technological innovation into the supply chain procurement process earlier.
- **Centralization of supply chain operations** across business units or particular products rather than within each business unit.
- **Consolidation** of the supply chain to reduce the overall number of suppliers and attendant complexity.
- Greater emphasis on **collaborative partnerships** with a select number of strategic suppliers, and a more solutions-oriented approach to suppliers in general.
- **Shorter lead times** overall and highly responsive supply chains to meet customer demands that can't be anticipated ahead of time.
- Increasing **globalization of the supply chain** such that supplies can be sourced from firms in any corner of the world as long as the firms are cost competitive and deliver quality products on time.
- Instances of firms **moving production back to the United States** where the manufacturing environment is becoming more competitive, particularly given the emphasis on shorter lead times.

These changes directly impact SMEs within supply chains. The standard requirement for top suppliers today is to perform well in quality (e.g., deliver products that meet certification requirements with zero defects), cost (e.g., able to offer yearly price reductions), and time (e.g., able to achieve 100% on-time delivery). This can be accomplished through the application of lean practices and high-performing managerial capabilities, including an enthusiasm for problem solving.

In contrast to OEMs, **SMEs** generally have the weakest links within the ecosystem. This is in part because they have historically been on the receiving end of knowledge flows from their large customers. As a result, their ability to drive knowledge and ideas toward the OEMs has been limited and highly dependent on the OEM. SMEs also generally have weak links to universities and to the startup community.

Universities have relatively strong links with large OEMs and with the startup community, but limited engagement with SMEs. They tend to be active in both basic and applied R&D but are often looking 10 to 15 years out in terms of new technological developments. Nevertheless, the Commonwealth has many applied R&D centers that are focused on today's manufacturing challenges.

Finally, the vibrant community of **startups** is an important source of innovation in advanced manufacturing, particularly for OEMs. At the same time, OEMs can also be useful to startups as they attempt to scale up. The strength of the link between startups and OEMs depends in part on the nature of the industry and on the extent to which OEMs are receptive to, and actively engaging with, the startup community. Links between startups and SMEs, by contrast, are generally not strong in the region and based on *ad-hoc* interactions.

Germany provides an interesting case study for Massachusetts and for the U.S. as a whole with respect to strengthening SMEs in the manufacturing ecosystem. Arguably the most important mechanism for fostering innovation among German manufacturers, particularly among SMEs, is through **industry–university applied research consortia** that require SME participation.

4. Manufacturing Intermediaries in the Commonwealth are Primarily Focused on "Point Solutions" and on the Supply Side

Massachusetts is rich in intermediaries that provide, among other things, services and advice to SME manufacturers throughout the state. This assistance takes six primary forms: (1) process improvements, (2) workforce training, (3) strategic technology and cluster development, (4) technical and engineering process support, (5) managerial and professional education, and (6) marketing. However, the current system tends to focus on "point solutions"—such as supporting SMEs on a one-on-one basis primarily in workforce training, lean practices, and certification. This is necessary but not sufficient in terms of building innovation capacity. State efforts to support SMEs also focus primarily on the supply side—i.e., on workers and suppliers—often without enough input from the OEMs that drive the demand side. In addition, despite investments in some emerging technologies, Massachusetts lacks an overall strategic vision for advanced manufacturing that looks out five to ten years in terms of supply chain developments, technology road maps, and talent and training needs.

Recommendations to Improve the Innovation Ecosystem

Based on these findings, we identify four distinct areas of opportunity for improving the Massachusetts manufacturing innovation ecosystem, particularly for SMEs. They involve a statewide manufacturing strategy and agenda, OEM collaboration, technological and managerial support, and connections with startups. Our recommendations in each of these four areas are summarized below.

Advanced Manufacturing Strategy and Agenda

1. Develop an Advanced Manufacturing Strategy for the State

In contrast to the state's other cluster-focused strategies (e.g., for the biotech industry), advanced manufacturing requires the development of cross-cutting capabilities that work across industries. This makes it more challenging to develop strategies around particular capabilities. A deep understanding of advanced manufacturing capabilities, their importance within key clusters, and trends in technology as well as in the global manufacturing marketplace is required.

A robust analysis of the state's advanced manufacturing capabilities combined with engaging key manufacturing leaders in the state is necessary to develop an advanced manufacturing strategy and agenda for the next five to ten years. This includes involving relevant stakeholders and establishing appropriate governance structures to oversee such an effort.

2. Introduce Consortium-based Applied Research Projects

Grant funds should be used to encourage regional consortium-based projects including Universities, OEMs, and SMEs that focus on pre-competitive product and process innovations, similar to the German model. Experience in consortium-building in the process of applying for the federal Institutes for Manufacturing Innovation (IMIs) could be instructive in developing regional, project-based consortia.

Collaboration with OEMs to Drive Innovation and Upgrade SME Capabilities

3. Support the Formation of a Commonwealth Manufacturing Innovation Advisory Group

OEMs are a driving force for innovation in Massachusetts, yet their collective voice on the subject is not being heard. With a window into global trends, R&D opportunities, supply chain demands, and training needs five to ten years out, OEMs need to be engaged in helping set the state's manufacturing innovation strategy going forward. Their participation should be coupled with the participation of several high-performing SMEs, universities and others. A Manufacturing Innovation Advisory Group will promote long-term strategic thinking, collective action (and impact), and can highlight best practices for SMEs.

4. *Initiate a Collaborative OEM Supplier Upgrade Program*

Most OEMs have their own individual supplier development programs to help suppliers produce efficiently and meet the OEMs' delivery, cost, and quality requirements. However, there is little collaboration across OEMs in the same or different industries when it comes to upgrading the supplier base in the state, even when OEMs share similar suppliers.

Initiatives to upgrade supplier capabilities based on collaboration across OEMs from different industries could provide a robust mechanism for leveraging state resources, sharing best practices, and expanding support to SMEs. Such initiatives could focus not only on process and quality improvements but also on technical problem solving and workforce training.

5. *Introduce an Advanced Manufacturing SME Innovation Prize*

While several awards for small businesses are already offered in Massachusetts, a state-wide prize for innovative "world-class" advanced manufacturers would not only help set a high bar for SMEs and bring visibility to best practices for SMEs, it would also help change perceptions around advanced manufacturing in the state. The award could be given by a jury comprised of representatives from OEMs, universities, and intermediary organizations who are in a position to identify and evaluate particularly motivated and innovative SMEs.

Technological and Managerial Support for Innovation in SMEs

6. *Provide Technological and Engineering Support*

Thus far, state efforts to support SMEs have largely revolved around workforce training and lean practices. Such practices can lead to greater efficiency and accuracy in terms of quality, cost, and time. However, lean practices are a necessary but not sufficient requirement for success in today's global manufacturing environment. With the rise of new technologies, such as additive manufacturing, programs to support SMEs and build their innovation capacity need to go further. Specifically, support should be expanded to include centers, either existing or yet to be formed, that provide technological and engineering services to SMEs engaged in product and process innovation.

7. *Better Promote and Increase Awareness of Support Services for SMEs*

Although numerous support programs and intermediaries exist in Massachusetts, many SMEs we interviewed were not aware of the portfolio of manufacturing services available in the state. Multiple factors may account for this lack of awareness, but it speaks to the larger challenge of creating an ecosystem that is well connected and where knowledge flows freely. A coordinated communications effort among the various intermediaries that work in this area could help highlight and promote existing support programs and resources within the larger manufacturing ecosystem.

8. *Support Executive Education Programs for SMEs*

Advanced manufacturing SMEs are under constant pressure to improve efficiency and innovate. Being "world class" today requires not only a culture and practice of lean, but also sound managerial infrastructure and leadership, combined with a culture and practice of continual product and process innovation.

An executive education program offered by prestigious business and management schools in the state and focused on operations management would help SMEs rise to this challenge and meet a high bar for managerial excellence. Such a program could be offered on a competitive basis and could provide matching funds to support executive education for CEOs and managers at highly motivated SMEs.

Connections between Startups and the Innovation Ecosystem

9. *Better Promote and Connect SME Capabilities in Early-Stage Scale-Up to the Startup Community*

Many Massachusetts startups, let alone startups outside Massachusetts, are unaware of the deep capabilities that exist within the state to support early-stage prototyping and piloting. Startups currently find manufacturing support through an ad-hoc, word-of-mouth process. Efforts by SME trade associations and intermediaries to better communicate these capabilities, together with a more explicit, systematic effort to connect SMEs and startups, is required.

10. *Connect Startups with OEMs for Beta Testing and Piloting*

In general, we found it difficult to assess the relative strength or weakness of current links between the Massachusetts startup community and large OEMs in the state. What is clear is that startups are almost always interested in stronger partnerships with potential customers and that more could be done to facilitate such partnerships within the region. Several efforts already exist in particular industries within the state—such as energy and financial services—but more explicit efforts could be geared toward advanced manufacturing-related technologies (e.g., robotics, advanced materials), where development time horizons are longer and where capital requirements during scale-up are higher.

Together these ten system-level recommendations are intended to increase the innovation capacity of the Commonwealth's manufacturing ecosystem through strengthening the links between key nodes within the system. Such steps will build long-term capabilities and institutions for the future that focus on frontier technologies, managerial and operational excellence and connectivity within the ecosystem to ensure Massachusetts' place as a world-class leader in advanced manufacturing.

2 Introduction

Recent years have brought a renewed focus on the importance of manufacturing to the health and future growth of the U.S. economy. Indeed, several studies and public-private initiatives have highlighted the need to maintain and build manufacturing capabilities to support economic growth, good jobs, and national security. Perhaps most importantly, they have linked the nation's **manufacturing capabilities to its ability to innovate**. Advanced manufacturing is essential for developing new products and processes across a range of industries, both established and emerging. As others have pointed out, the loss of these capabilities can shift an industry's center of gravity as higher value-added activities follow manufacturing abroad.

In few states is the link between manufacturing and innovation more evident than in Massachusetts. While manufacturing represents only 9 percent of employment in the Commonwealth (approximately 250,000 jobs), compared to 11 percent in the country overall, it is integral to several of the **state's most important industries,** including aerospace/defense, semiconductors and computers, biopharmaceuticals, and medical devices. Massachusetts manufacturers compete globally on their innovation capacity, high skills, product quality, and rapid response.

Small and medium-sized enterprises (SMEs) play a critical role in maintaining and growing the manufacturing strengths of the U.S. and Massachusetts economies. These companies are the **"backbone"** of the country's and the region's industrial capabilities and they exist in every community where manufacturing takes place. SMEs supply both the large established firms (known as "original equipment manufacturers" or OEMs) that regularly develop sophisticated products and systems and the entrepreneurial firms that engage in prototyping or pilot production to advance new products.

This report focuses on opportunities for building innovation capacity within the Massachusetts manufacturing ecosystem and, in particular, on how the state can best **support SMEs in their efforts to be globally competitive**. Manufacturing capabilities are grounded in particular regions, where, historically, they have grown around key industries—examples include the automotive industry in the Midwest or turbine engines and firearms in Massachusetts. Thus, manufacturing lends itself to regional approaches for increasing innovation capacity and upgrading firms' capabilities. Strengthening the regional innovation ecosystem as a whole will improve the "industrial commons" [2] and leverage greater results by helping all manufacturers in the state, not just a select few.

This is particularly important for SMEs. Recent research by MIT's Production in the Innovation Economy (PIE) project [3] concluded that SMEs often find themselves **"home alone"** when it comes to competing globally and driving innovation in their companies. The large, vertically-integrated corporations of the 1980s have tended to become less vertically integrated over time as they sought to focus on their core competencies, outsourced much of their production and increasingly relied on smaller suppliers to drive innovation. This process has left **"holes" in the industrial ecosystem**, cutting off many of the important investments and spillovers that used to flow from large corporations to smaller firms (e.g., in training, technology adoption, and R&D investments). As a result many SMEs have been left largely on their own to figure out how to find and train workers, adopt new technologies, and develop and scale new products and services, while shouldering the burden of funding this at the same time.

This report focuses on how to fill these holes as they relate to innovation. We used **a systems approach** that considers how knowledge and sources of innovation flow between key participants within the manufacturing innovation ecosystem. Strengthening these links and expanding the flow of knowledge between key actors will upgrade the system as a whole and enhance the region's competitiveness. As other regions and countries around the world increase investment in manufacturing and incentives for manufacturing firms, it is increasingly important for Massachusetts to leverage and invest in its own innovation assets to fully **establish the state as a world-class** leader in advanced manufacturing.

Report Methodology and Outline

The objective of this research is to find pathways and opportunities for building and fostering innovation capacity among Massachusetts manufacturers, with a particular focus on small and medium-sized companies. To that end, we have sought to develop a deep understanding of the current manufacturing landscape and of the intermediary systems that support manufacturing in the Commonwealth. We carried out a quantitative analysis of the state's industrial base and also developed qualitative findings based on interviews with relevant actors in the innovation ecosystem. As part of this latter effort, we included interviews conducted in Germany for benchmarking purposes.

The research effort described in this report involved seven main tasks (see Figure 10 and additional details in the appendix):

- A review of **relevant studies,** both national and regional.
- An analysis of the **manufacturing base** in Massachusetts to obtain a picture of the most important manufacturing sub-industries. The analysis relied on data retrieved from public and private databases (e.g., Bureau of Labor, U.S. Census Bureau, OneSource, etc.) and was used to select several specific industries and sub-industries as the focus of this research.
- Interviews with **SMEs and OEMs**. Our process for identifying companies to interview (see Figure 11 in the appendix) began with the identification of the largest OEMs within each focus industry. Interviews with these OEMs helped us identify some of their top small suppliers. Additional SMEs that are considered high performing and innovative, or that are on a path to becoming so, were identified from several different sources, including the Workforce Training Fund, ISO certifications, and collaborations with universities. SMEs on at least two of these lists were selected for interviews. Additionally, we interviewed a few companies that were identified by experts in the field as high performing and innovative.[1]
- An effort to define the **requirements and success factors** for innovative SMEs in today's global manufacturing economy.

[1] For a full list see Table 11 the appendix.

- A review of **the landscape of intermediary firms and organizations** and of the policies and programs that exist, in Massachusetts and elsewhere, to support manufacturers.
- Work to develop a set of **recommendations** for both the public and private sector.

The remainder of this report is organized as follows. Section 3 defines key terms. Section 4 provides an overview of the manufacturing base in Massachusetts. Section 5 describes the manufacturing innovation ecosystem that exists today, identifying the key actors and outlining the opportunities and challenges they face operating in Massachusetts. Section 6 considers the intermediary landscape. Section 7 summarizes findings. Section 8 presents recommendations and Section 9 provides a conclusion.

3 Defining Terms and Trends in Advanced Manufacturing

This section provides general definitions of key terms that are used throughout the report, describes trends in advanced manufacturing, and provides an overview of some recent national- and state-level studies that are relevant to the issues discussed in this report.

3.1 Definition of Key Terms

We begin by defining a term that is frequently used and often poorly specified: innovation. According to one source, **innovation** refers to "the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations." [4] Innovation differs from invention. Invention is the creation of something new and novel while innovation is the process of adding value to an invention such that it becomes useful in the marketplace [5].

There are four different dimensions to innovation (Figure 1). **Product or service innovation** is the first-time commercial utilization of a product or service that is new to the market.

Process innovation is the implementation of methods that are new to the company—not necessarily new in the market—and that change the way a company manufactures a product. Process improvement measures, like lean manufacturing, Six Sigma, etc., are often included in this category of innovation, though they may be less about true innovation and more about continuous improvement.

Organizational innovation is the implementation of new organizational methods within a firm that change the firm's business practices, communication, and/or workplace organization. The latter two innovation dimensions have a clear company perspective.

This study is primarily focused on product and process innovation.

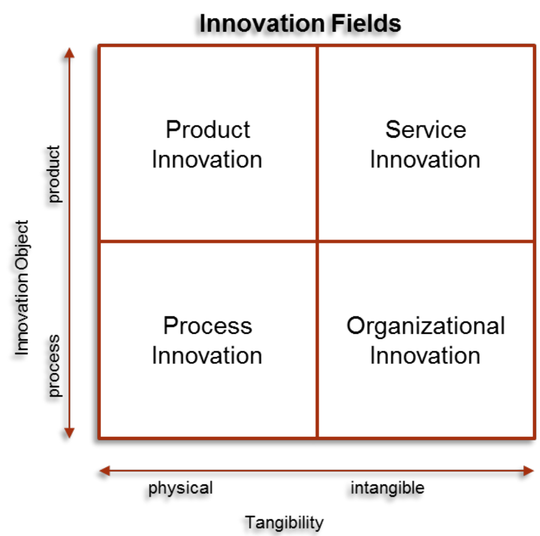

Figure 1: Dimensions of Innovation [6]

The term **"advanced manufacturing"** refers to the use of next-generation technologies in manufacturing processes. Specifically, advanced manufacturing "makes extensive use of computer, high precision, and information technologies integrated with a high performance workforce in a production system capable of furnishing a heterogeneous mix of products in small or large volumes with both the efficiency of mass production and the flexibility for custom manufacturing in order to respond rapidly to customer demands." [7] More precisely, advanced manufacturing encompasses "a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences. It involves both new ways to manufacture existing products and the manufacture of new products emerging from new advanced technologies." [8]

"Innovation ecosystem" is a term that has gained popularity in recent years. The "ecosystem" metaphor draws from our understanding of natural ecosystems and of their ability to sustain a population when all members of the community are contributing. The idea of an "innovation ecosystem" is rooted in part in the literature on "national innovation systems" [9]. A national innovation system (NIS) is defined most succinctly as "the set of institutions whose interactions determine the innovative performance of national firms." The term "ecosystem" adds a more dynamic element to the system concept [10].

Regional **capabilities** are another important concern for this study. Dynamic capabilities, at the firm level, refer to a company's ability to respond to market opportunities and new scientific and technological advances with new products and processes that call on the firm's own internal organization and production methods. Our discussion of regional capabilities draws from the concept of firm-level capabilities and integrates it with the concept of regional specialization, which is based in cluster theory. [11] [12] Regional capabilities speak to a region's ability to develop new products and processes over time based on the capacity of entrepreneurial firms within the region.

Small and medium-sized enterprises (SMEs) refer to firms with fewer than 500 employees. Interestingly, the U.S., unlike Europe, does not use revenue to define SMEs. [13]

Original equipment manufacturers (OEMs) are "firms that [...] manufacture [...] based on 'original' designs." [14] OEMs either make products directly or act as a system integrator before selling directly to the customer. Throughout this study, the term OEMs typically refers to large enterprises, with over 500 employees.

3.2 Trends in Advanced Manufacturing

The marriage of hardware and software, and the use of new information technologies combined with advanced machinery to increase automation, intelligence, efficiency, and sustainability in manufacturing processes is at the heart of recent developments in advanced manufacturing. In 2013, Germany launched its "Industry 4.0" initiative with a primary focus on the systematic interconnection of existing manufacturing systems in the new "facility of the future" (machinery, information systems, employees, regulation, standardization) [15] in order to develop self-organizing autonomous manufacturing systems (see Table 3 in the appendix). In the U.S., the Smart Manufacturing Leadership Council has adopted a slightly different emphasis, albeit with similar goals. The Council is focusing on the need to develop new standards and platforms for a common information technology infrastructure that would include, for example, data collection systems and community simulation platforms [16] for new advanced manufacturing technologies.

More broadly, in two reports to the President's Council of Advisors on Science and Technology (PCAST) in 2012 and 2014, the Advanced Manufacturing Partnership (AMP) [15], an industry-academia-government partnership, put forward several recommendations for boosting innovation in advanced manufacturing in the U.S. through the creation of new R&D infrastructure and technology road maps. The National Network for Manufacturing Innovation (NNMI), which was launched in 2012, represents the country's most significant investment in advanced manufacturing in recent history. It includes several centers that are supported and led by public-private consortia and that focus on the development of pre-competitive technologies while also building regional capabilities in their focus areas: [17]

- Institute for Advanced Composites Manufacturing Innovation (Knoxville, TN)
- Digital Manufacturing & Design Innovation Institute (Chicago, IL)
- Lightweight Innovations for Tomorrow (Detroit, MI)
- PowerAmerica—Wide Bandgap Semiconductors (Raleigh, NC)
- America Makes—Additive Manufacturing (Youngstown, OH)
- Flexible Hybrid Electronics (in progress)
- Smart Manufacturing (in progress)
- Integrated Photonics Institute (in progress)

The recent AMP 2.0 report in 2014 highlighted three additional focus areas for future national efforts in manufacturing innovation: (1) advanced sensing, control and platforms in manufacturing; (2) visualization, informatics and digital manufacturing; and (3) advanced materials manufacturing.

Several **national studies** are relevant to this report, including the aforementioned AMP reports to PCAST in 2012 and 2014 [18], MIT's 2013 *Production in the Innovation Economy* study [3], and a recent (2015) report on supply chains by the U.S. Department of Commerce [19], among others. These national reports address a range of important issues such as enabling innovation, improving training and the talent pipeline, strengthening supply chains, and generally rebuilding the industrial ecosystem while improving the overall business environment.

At the **local and regional level**, recent reports specific to Massachusetts focus primarily on the needs of SME manufacturers and on the state's business environment. They highlight the high need for more skilled workers, the cost of doing business, the need for technical assistance and innovation support, the importance of access to capital, and the value of a better image for manufacturing (see Table 4 in the appendix for a full list of the reports). Although these regional studies provide detailed information about the manufacturing base in Massachusetts, a comprehensive analysis of the **manufacturing innovation ecosystem** has not been the focus of regional work to date.

4. The Massachusetts Manufacturing Base

This section provides an assessment of the competitive position of manufacturing in Massachusetts, reports on a quantitative analysis of employment and establishment data, and describes the basis for selecting particular focus industries for the study.

4.1 The Competitive Position of Manufacturing in Massachusetts

Massachusetts offers an important case study of how small U.S. manufacturers compete in today's global economy and complex supply chains. The Commonwealth has a diverse and sophisticated manufacturing base that includes about 7,000 firms in a wide range of industries, including aerospace/defense, semiconductors/electronics, medical devices, and biopharmaceuticals [20]. SMEs with fewer than 100 employees account for about 92% of the manufacturers in the state [21]. The vast majority of these firms participate in regional, national or global supply chains. However, SMEs account for only approximately 30% of the state's manufacturing employment [22].

Massachusetts has a long and illustrious history in manufacturing and in product and process innovation [1], and the **advanced manufacturing capabilities** it built over the past 150 years have allowed companies and workers to transition into new or emerging industries as market conditions change. In fact, one of the region's strengths is a diverse manufacturing base that supports **cross-fertilization** among its key clusters.

Manufacturing employment has steadily declined over the past several decades (see e.g., [20]). Since the 1990s manufacturing jobs have declined as a share of the state's overall employment from approximately 19% to about 9% today (this compares with a national-level figure of about 11% in 2013, down from 20% in 1990 [23]), where the current data reflect some recovery from the depths of the Great Recession in 2008. The decline in the share of manufacturing jobs at the state level mirrors national trends for the U.S. as a whole, and global trends for other industrialized countries as productivity rates have increased, production has become more fragmented, and global competition has intensified.

While Massachusetts manufacturers are undoubtedly operating in an increasingly complex environment, this new environment also offers opportunities for those SMEs who can **compete on a "world-class" basis.** More intense global competition, the development of new generations of advanced manufacturing technologies, and novel ideas about how to organize manufacturing firms and facilities and better deploy workers are creating challenges and new possibilities for advanced manufacturing SMEs.

Despite the fact that a significant number of Massachusetts SMEs are engaged in contract manufacturing of what are often termed (misleadingly) "commodity products," OEMs consistently referenced the following attributes as key characteristics of the state's manufacturing production system:

- Small-batch niche production, rather than large-volume mass production;
- Extremely high quality and performance requirements (zero percent failure);
- High knowledge and innovation content;
- New or early-stage products and prototyping;
- Products with high proprietary content;
- Products where proximity to market is desirable;
- Products where regulatory factors encourage siting in the U.S.; and
- Customized products with quick turnaround time if needed.

To sustain these characteristics, OEMs can draw on four primary assets:

- A well-educated and **highly skilled labor force**, particularly in engineering;
- Suppliers that are able to quickly provide difficult-to-manufacture **parts of very high quality and reliability**;
- World-class **universities**; and
- Innovative startups and a dynamic entrepreneurial ecosystem.

For all these reasons, Massachusetts manufacturing base has stabilized since the 2008 crisis and remains strong today. Indeed, the state's manufacturers are well positioned to take advantage of some of the national and global trends that suggest the U.S. may be more globally competitive in manufacturing in the future. In particular, declining energy costs, rising labor costs in traditionally low-wage countries, and concerns about the protection of intellectual property are making the U.S. environment **more competitive** for certain types of manufacturing, including those in which Massachusetts excels. In addition, the development of **new "game-changing" advanced manufacturing technologies** such as additive manufacturing, cyber-physical systems, and integrated circuit photonics, is providing additional opportunities for U.S. firms to innovate and increase efficiency.

4.2 The Massachusetts Manufacturing Base

Manufacturing in Massachusetts was adversely affected by the recessions of 2000 and 2008, which caused the state to lose 40% of its manufacturing employment base and 30% of manufacturing establishments (Figure 2 and Figure 3). In terms of employment, Massachusetts followed the national trend with a sharp decline in manufacturing jobs in 2008 and 2009, followed by a stabilizing of the employment picture in 2010 at approximately 250,000 workers and 7,000 establishments.

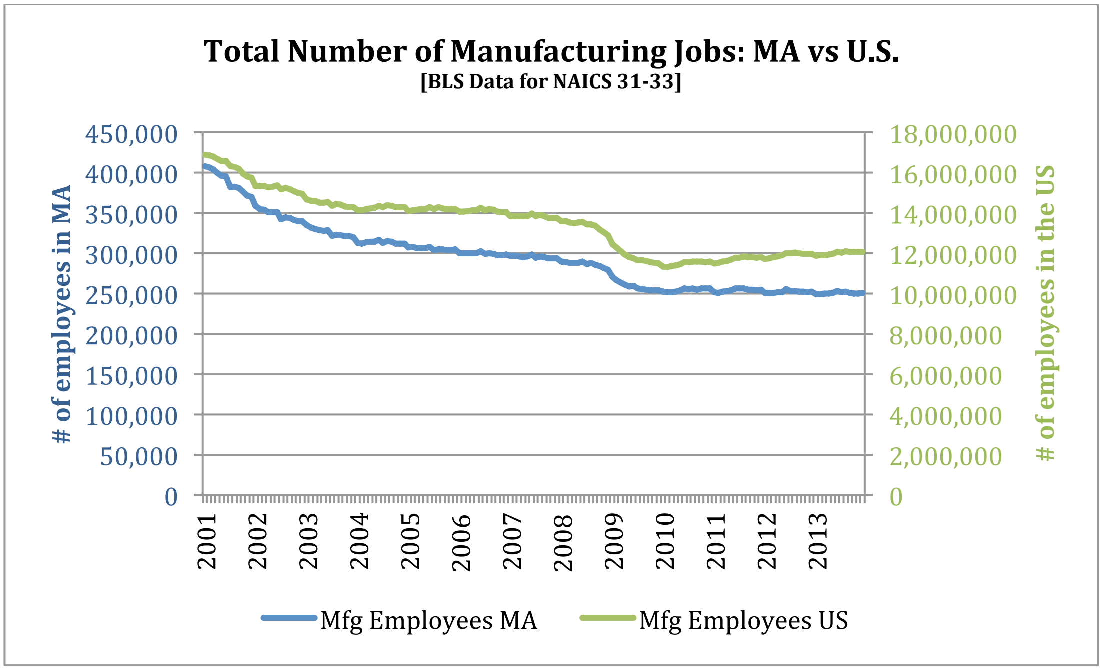

Figure 2: Total number of jobs in the manufacturing industry in Massachusetts and in the United States between 2001 and 2013

In terms of manufacturing establishments, Massachusetts experienced a steady decline from about 10,000 establishments in 2001 to about 7,000 in 2013, for a total contraction of about 30%—twice the national rate. The total number of U.S. manufacturing establishments fell from about 400,000 in 2001 to about 335,000 in 2013.

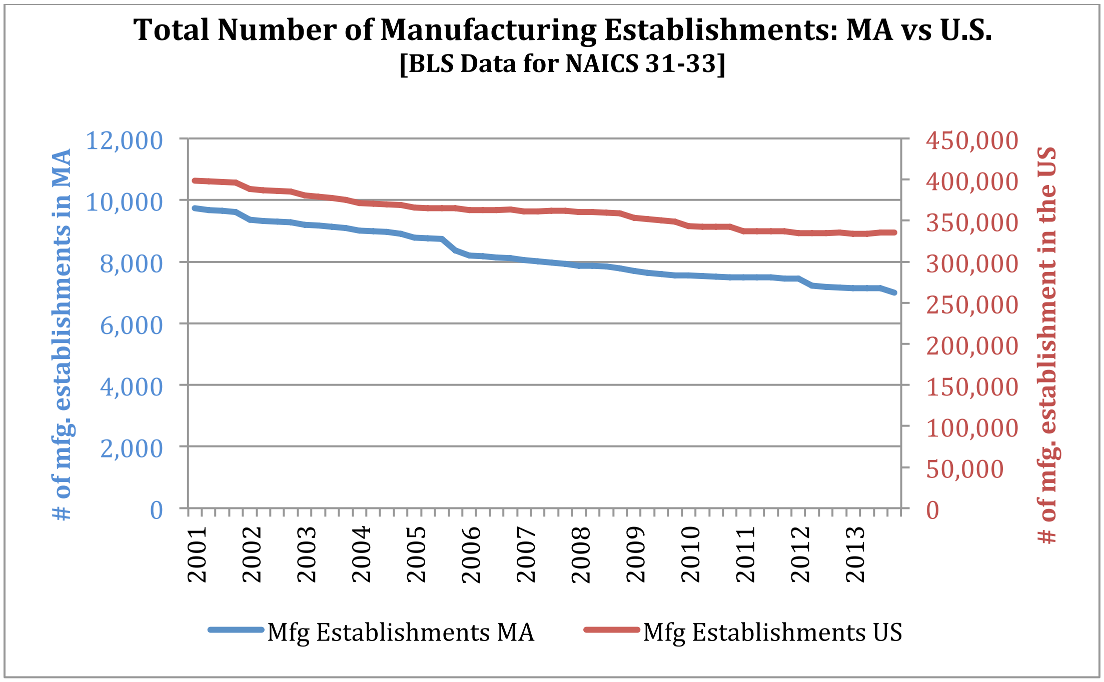

Figure 3: Total number of establishments in the manufacturing industry in Massachusetts and in the United States between 2001 and 2013

Approximately 97% of all manufacturing establishments in Massachusetts can be considered SMEs (i.e., firms with fewer than 500 employees) [22] and about 92% have even fewer than 100 workers. [21]. Although SMEs vastly outnumber large firms, they account for only 30% of all manufacturing jobs. Large firms, though they represent only approximately 3% of all manufacturing establishments, account for 70% of manufacturing employment in the state [22].

Defining Advanced Manufacturing Industries

Massachusetts has a diverse set of manufacturing industries and sub-industries that support some of the state's key sectors.[2] These sub-industries create foundational **cross-cutting capabilities** within the regional economy. This section outlines our methodology for defining what constitutes "advanced manufacturing" in the Commonwealth and for selecting specific industries to focus on in this report.

The typical approach used to analyze industrial composition in the United States relies on North American Industry Classification System (NAICS) codes. Each firm is assigned a code based on how it self-identifies under one or more industrial classifications.[3] While the NAICS codes provide a standard way to organize and report employment, establishment, and wage data, they also have limitations. In particular,

[2] Throughout this report the term industries refer to the four-digit NAICS subsectors, the term sub-industries refer to the six-digit NAICS subsectors, and key sectors comprise according to [22] several related industries.

[3] NAICS has three categories for capturing the manufacturing industry (codes 31 to 33). Each industry code gets more granular down to a six-digit level. For a general understanding of the manufacturing sector in the state, a four-digit analysis is sufficient (and generates seven manufacturing categories for our analysis). For an understanding of what constitutes advanced manufacturing in the state, the six-digit level analysis is appropriate (in which we used ten sub-industry categories). Likewise, for the general development of the manufacturing industry in Massachusetts, the four-digit level is appropriate whereas for the definition of the focus advanced manufacturing industries, the six-digit subsectors should be used.

NAICS codes do not capture cross-cutting capabilities or technologies, such as advanced materials, precision machining, photonics or robotics, that exist across industries.[4]

Recognizing that almost all modern manufacturing involves some advanced elements, we used three filters to help determine which manufacturing sub-industries could be considered especially advanced or innovative (Figure 4). Starting with NAICS codes at the four-digit level, we considered:

- Patent data as a proxy for innovation, albeit one that is not particularly well suited for manufacturing (Table 7 in the appendix);
- R&D spending per worker and share of STEM (science, technology, engineering, and math) occupations (Table 8 in the appendix); and
- Employment data (Table 9 in the appendix).

Based on these filters we reduced the number of relevant manufacturing industry categories from 86 to 7. These seven remaining industries also have above-average location quotients,[5] emphasizing the relative importance of these industries in the state compared to their relative importance nationwide.

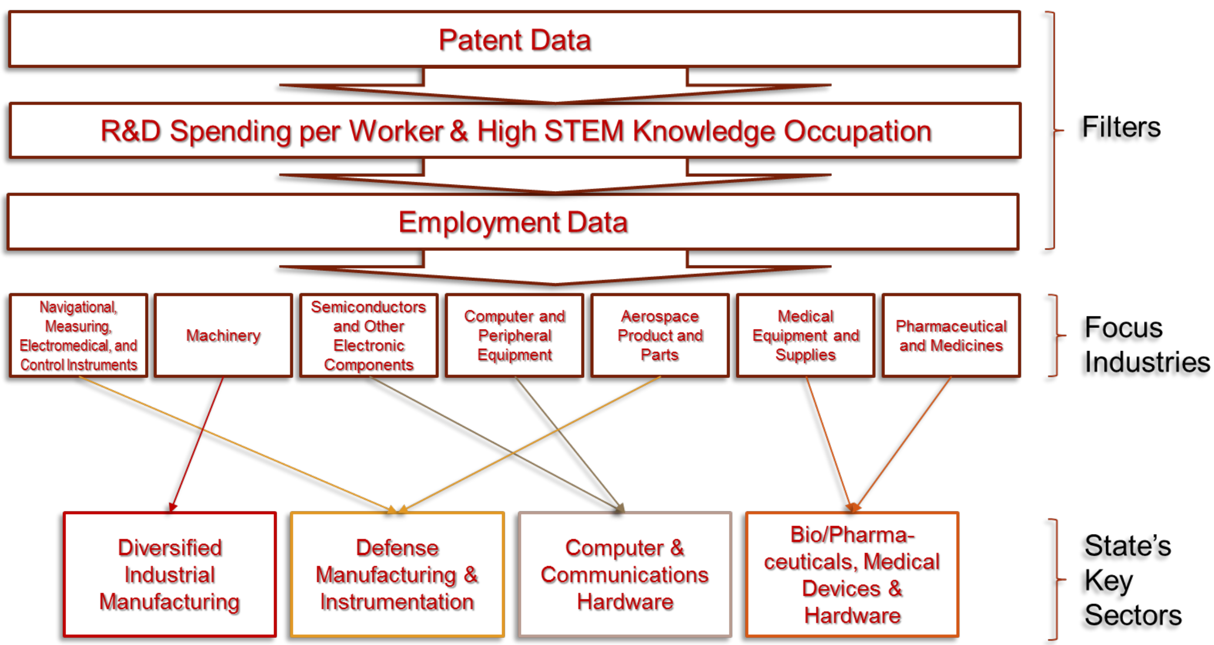

Figure 4: Procedure for defining focus industries and their relationship to key sectors in Massachusetts

[4] A robotics company such as iRobot, for example, is found in 335210 - Small Electrical Appliance Manufacturing.
[5] Location quotients (LQ) are ratios that compare the concentration of the sub-industry (by employment) in a defined area (state) to that of a larger area (e.g. the U.S.) [58]. In this case, the LQ compares 4-digit NAICS sub-industries in Massachusetts with the same sub-industry in the U.S. as a whole. LQs greater than 1 suggest a higher than average concentration of that sub-industry.

These seven industries support several of the state's "key sectors" as defined by the Massachusetts Technology Collaborative's Innovation Institute (II MTC)[6] [24]. The same industries also pay the highest annual average wages per employee (see Table 10 in the appendix), reflecting the higher value-added and advanced nature of the jobs within these industries.

Ultimately, we delved into these seven industries down to the six-digit level NAICS codes to identify the nine advanced manufacturing sub-industries (out of 345) with the highest employment.[7] Figure 5 shows also the overall ranking of these sub-industries by employment.

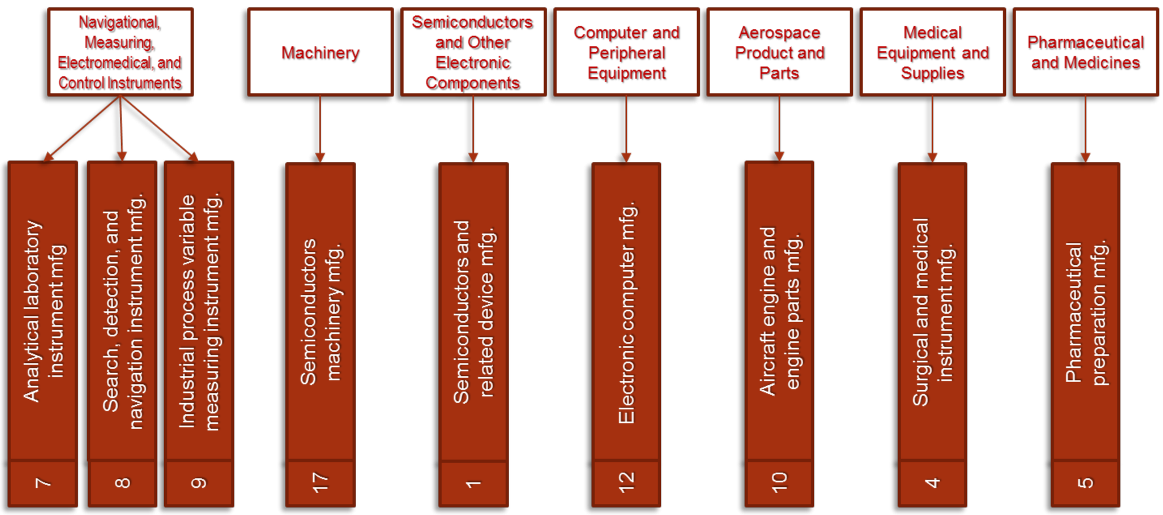

Figure 5: Sub-industries with the highest employment within the defined focus industries

We also included machine shops as a focus sub-industry, despite the fact that this type of enterprise was not identified in our filtering process. The companies in this category are primarily process specialists with no proprietary products. They are overwhelmingly SMEs with fewer than 100 employees (see Figure 14 in the appendix). Machine shops are a valuable part of the ecosystem and support all of the key manufacturing-related sectors of the economy. As a sub-industry they not only have one of the highest employment levels in the state, they are also important enablers of product innovation by OEMs, delivering high-precision, small-batch products with short lead times. Machine shops are also the sub-industry with the highest number of ISO-certified companies (see Figure 15 in the appendix) reflecting their commitment to high precision and quality.

Overall, the 10 manufacturing sub-industries we identified are primarily concentrated in the greater Boston area (Figure 6), although machine shops, designated in blue, are located throughout most of the state.

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[6] The II MTC defined 11 key sectors: Advanced Materials, Bio/Pharmaceuticals, Medical Devices & Hardware, Business Services, Computer & Communications Hardware, Defense Manufacturing & Instrumentation, Diversified Industrial Manufacturing, Financial Services, Healthcare Delivery, Postsecondary Education, Scientific, Technical & Management Services, and Software & Communications Services.

[7] The complete list of the top 20 sub-industries in terms of subsectors on the 6-digit NAICS level is available in the appendix in Figure 14.

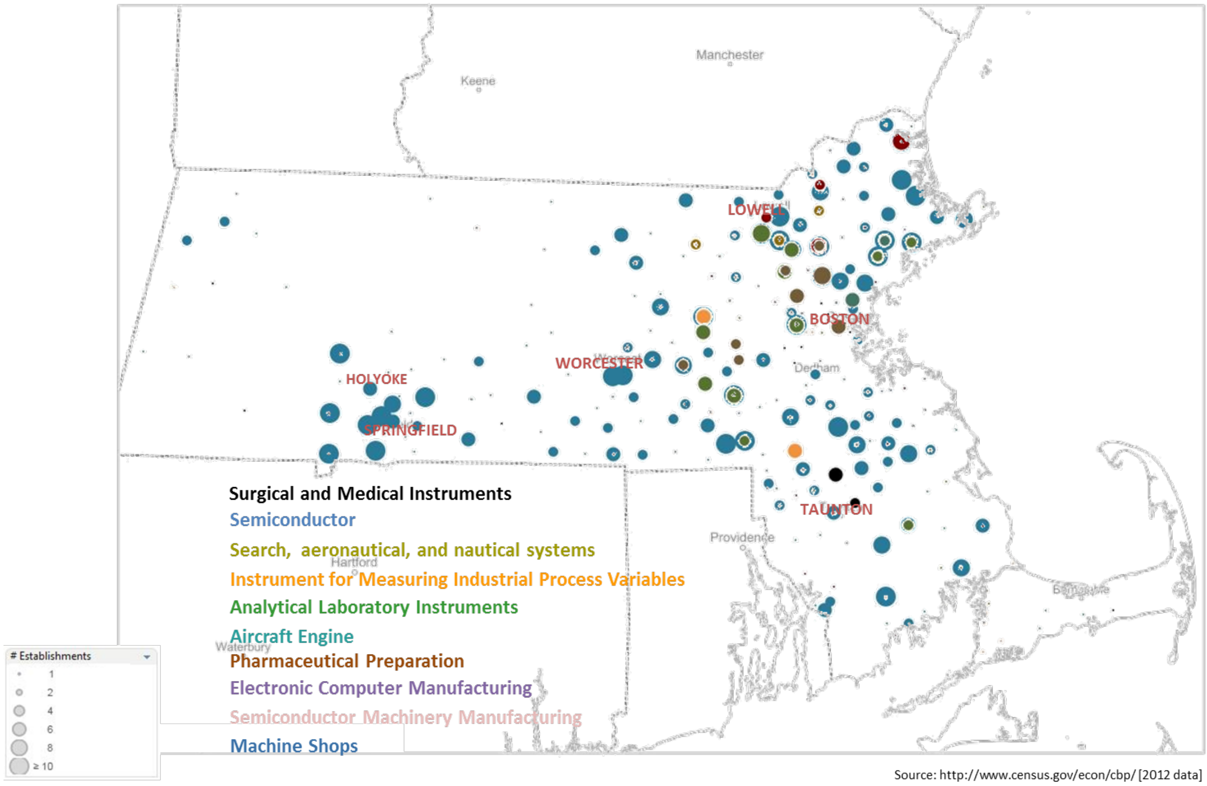

Figure 6: Geographical distribution of establishments in the focus manufacturing sub-industries

These ten sub-industries have some interesting similarities and differences (see Table 6 in the appendix). Some of them (i.e., Surgical and Medical Instruments Manufacturing, Pharmaceutical Preparation, and Industrial Process Variable Instruments Manufacturing) are very heterogeneous in terms of the business products and services they provide. There is less heterogeneity in other sub-industries (such as Machine Shops, Analytical Laboratory Instruments and Aircraft Engine and Engine Parts), which manufacture more precision-engineered commodity products. Several other points about the ten sub-industries are worth noting:

- There are relatively few SMEs in the Semiconductor sub-industry; 3% of all companies employ about 70% of all employees in this sub-industry (similar to the overall structure of the manufacturing industry as a whole, as discussed above).
- The Machine Shops sub-industry includes the largest number of SMEs, with about 630 establishments.
- In the Surgical and Medical Instruments sub-industry as well as in the Pharmaceutical Preparation sub-industry, SMEs operate in niches focused on specific surgical and medical needs or diseases respectively.
- In the Analytical Laboratory Instruments Manufacturing sub-industry, SMEs make largely "commodity" products.
- There are few SMEs in either the Search, Detection, and Navigation Instruments Manufacturing sub-industry or the Aircraft Engine and Engine Parts Manufacturing sub-industry.

- Most of the SMEs in the Industrial Process Variable Instruments Manufacturing sub-industry focus on light measurement systems; their main customers are research institutions and the military.

Overall, the seven focus industries and their nine sub-industries plus machine shops account, respectively, for 41% and 23% of manufacturing jobs and establishments in the Commonwealth. But they are potentially the industries that are most important to the state's economy in terms of driving and enhancing innovation.

5 The Massachusetts Manufacturing Innovation Ecosystem

The innovation process is often characterized as **non-linear and dynamic**, involving different actors with highly interactive relationships [25] [26]. While firm innovation might have occurred in isolation in the past, particularly when many firms were vertically integrated, today's firms have **high degrees of interaction** with a range of other companies and organizations, such as universities, suppliers, customers, and even competitors—all of which may play a part in building a firm's innovation capacity. External factors such as laws, regulations, culture, and technical standards also play an important role in setting the stage for innovative activities [27]. For these reasons, the process of innovation cannot be viewed through one single lens (within a single company or institution) but needs to be understood as part of a larger system [28] [29]. This is the approach taken in this study.

Based on our research, four key nodes and associated institutions and actors play a major role in the state's advanced manufacturing innovation ecosystem:

- Large OEMs,
- Supplier SMEs,
- Startups, and
- Universities and research institutions.

Figure 7 presents a stylized representation of these key drivers and actors. Obviously, the innovation system relies not only on flows between the four nodes depicted in the figure but also on knowledge that comes into the region from outside sources such as R&D networks, trade associations, and global partnerships/networks.

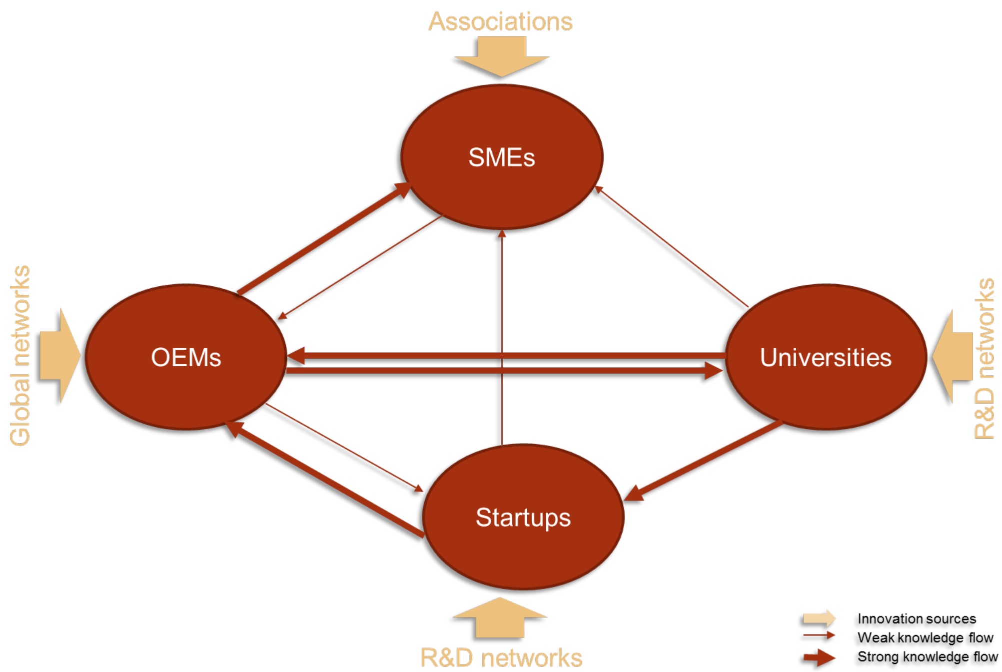

Figure 7: A schematic of the manufacturing innovation ecosystem in Massachusetts

The lines connecting each of the four nodes represent the general strength and direction of the knowledge flows between them.

In general, **OEMs have the strongest links** within the innovation ecosystem because they are largely driving innovation activities within it. Knowledge flows between OEMs and research universities are strong in both directions, while knowledge flows with SMEs are relatively unidirectional flowing from OEM to SME. With respect to innovation, startups typically bring new ideas to the OEMs.

In contrast to OEMs, **SMEs generally have the weakest links** within the ecosystem. Historically, they have most often been on the receiving end of knowledge flows from their large customers. Their ability to drive knowledge and ideas in the other direction, toward the OEMs, has been limited, though this is highly dependent on the OEM. SMEs also generally have weak links to universities and to the startup community.

Universities have relatively strong links with large OEMs and with the startup community, but **limited engagement with SMEs.** University research primarily drives "disruptive" innovation and is often focused 10 to 15 years out in terms of new technological developments.

Finally, the **vibrant startup community is an important source of innovation** for OEMs. The strength of the link between startups and OEMs depends in part on the industry and on the extent to which OEMs are receptive to, and actively engaged with, the startup community.

The next sections provide more details about each of the four nodes in the ecosystem and about the opportunities and challenges they confront with respect to increasing their innovation capacity.

5.1 OEMs within the Manufacturing Innovation Ecosystem

OEMs are the most important drivers of innovation in Massachusetts with connections to all other actors in the innovation ecosystem. Interviews with OEMs in our focus industries (see Section 4.2) suggested that OEMs draw on the region's capabilities in different ways depending on their industry structure, their development time horizons, and their regulatory environment. In all cases, OEMs consider the region a place for new product development and new product introduction as evidenced by the number of OEM advanced manufacturing R&D facilities located in the state (some company examples include Gillette, Medtronic, Thermo-Fisher, Raytheon, and more recently Nihon Kohden and Phillips Healthcare). For example:

- Semiconductors and electronics are largely manufactured in Asia and Mexico and then integrated into other products in the U.S.; there is some specialized production in the U.S. as well.
- The aerospace and defense industries require largely domestic production, but there is increasing pressure on OEMs to manufacture in the countries of their foreign customers.
- Manufacturers of measuring devices and medical devices are more likely to keep high-end production in the U.S.; they benefit from proximity to suppliers for rapid response and small-batch production.

As described earlier, OEMs manufacture in Massachusetts for reasons largely linked to innovation and talent. Access to innovation and talent helps the OEMs respond to increasing pressure to cut lead times and meet high quality standards. Interviews highlighted the following attributes of the Massachusetts innovation ecosystem:

1. The presence of **world-class research universities** with high-impact research groups gives OEMs the opportunity to support unique, business-related, cutting-edge research that can be integrated or translated into competitive products to gain market share.
2. Graduates from the state's research universities constitute an **important talent pool** for large OEMs as they seek to develop new or improve existing products, services, processes, or organizational structures.
3. Besides universities, the state's vibrant **startup community** is a source of new ideas for products and services; in addition, collaboration with or acquisition of business-related startups can open new market opportunities.
4. To rapidly introduce new products, OEMs in Massachusetts can rely on **flexible, quick, and reliable suppliers**, especially machine shops that can manufacture special parts and components on a small scale.

At the same time, OEMs in Massachusetts face several key innovation challenges:

1. While a well-educated, highly skilled labor force is one of the Commonwealth's major strengths, OEMs are emphatic that **access to labor remains a serious problem**. This is an area where Massachusetts is under strong pressure from other regions. Several OEMs expressed the view that the supply of labor – including skilled labor – was better in the South, and in some cases better abroad (especially in Mexico).
2. The younger generation's **perception of manufacturing** jobs is out of date and needs to be updated to reflect the clean, technologically advanced nature of the industry. The Massachusetts manufacturing community is acutely aware of the problem of skilled labor shortages and has taken a number of actions in response, including strengthening its outreach to community colleges and local organizations to promote manufacturing as a viable career, and revising and standardizing training programs to facilitate skills acquisition.
3. The **importance of government's role** in attracting or retaining manufacturing investments cannot be ignored. Some U.S. states have taken a very aggressive approach in trying to attract manufacturing jobs, actively recruiting manufacturing firms and offering significant incentives to locate manufacturing facilities in their state. Further, governments of many developing or emerging economies (e.g. South Korea, Turkey, Brazil, the Middle East) require suppliers to set up operations in the country if they would like to do business there. U.S.-based OEMs have often responded to such requests without moving essential manufacturing but these kinds of *quid pro quo* or offset pressures are increasing. Finally, several OEMs perceive that China is progressively losing its attractiveness as a low-cost manufacturing location because of rapid wage escalation, poor workforce stability, and the total costs of addressing intellectual property protection.

Several important efforts are already underway in Massachusetts to address the issue of labor supply and training and to begin changing perceptions about the nature of manufacturing jobs. The **Manufacturing Advancement Center Workforce Innovation Collaborative** (MACWIC), for example, is collaboratively tackling urgent issues, like workforce training. The MACWIC program is employer-led; it comprises not only companies, both small and large, but also education/technical training providers as well as the Massachusetts Manufacturing Extension Partnership (MassMEP) and it aims to identify and find solutions to workforce-related needs. The Collaborative's most important output to date is a five-tiered training pyramid consisting of stackable consecutive training modules that can be offered jointly by vocational and technical high schools and community colleges. Students can take these modules to earn an Associate Degree in Manufacturing Technology. The industry-driven and modular nature of the program enables employers to better evaluate the level of graduates' skills. [30]

5.2 Trends in OEM Supply Chain Management

Over the past five to ten years, many OEMs have undergone a significant reorganization and rethinking of their supply chains. Pressure from customers, in most cases to reduce costs, has forced OEMs to rethink how they can best drive greater efficiency and innovation in the supply chain. The discussion in this section draws from extensive interviews and roundtable discussions with senior OEM managers in Massachusetts.

These managers point to several important changes in the supply chain in recent years:

- **Integration** of supply chain management with engineering to bring design and technological innovation into the supply chain procurement process earlier.
- **Centralization** of supply chain operations across business units or particular products rather than within each business unit.
- **Consolidation** of the supply chain to reduce the overall number of suppliers and attendant complexity.
- Greater emphasis on **collaborative partnerships** with a select number of strategic suppliers, and a more solutions-oriented approach to suppliers in general.
- **Shorter lead times** overall and highly responsive supply chains to meet customer demands that cannot be anticipated ahead of time.
- Increasing **globalization** of the supply chains such that supplies can be sourced from firms in any corner of the world as long as they are cost competitive and deliver quality products on time.
- Instances of firms **moving production back** to the U.S. where it is becoming more competitive to manufacture, particularly given the emphasis on shorter lead times.

These changes directly impact SMEs within the supply chain. OEMs generally recognize that it is not in their long-term interest to squeeze their own suppliers to the extent that the supplier's business is put at risk. On the contrary, they want to build a strong supplier base that is reliable and can work with them over the long term. At least one of the OEMs we interviewed actively encourages its suppliers to diversify and serve different industries so that the suppliers are not solely dependent on one company or industry.

Whether suppliers are SMEs or other very large companies, OEMs recognize them as crucial to their own business success, especially as ever more activity is outsourced. OEMs emphasize that they seek deep, strategic relations rather than transactional relations with their key suppliers, i.e., with suppliers they rely on to provide hard-to-source, mission-critical technology or components.

> *"We've gone from "80% make 20% buy" in the 1980s to "20% make 80% buy" today."*
>
> OEM in Aerospace/Defense

These strategic suppliers are at the top of a pyramid that illustrates the stratification of suppliers according to their value added as it relates to innovation (Figure 8). By contrast, most of the base of the pyramid is made up of commodity and bottleneck suppliers who provide parts and components that are less critical than the parts and components made by strategic suppliers.

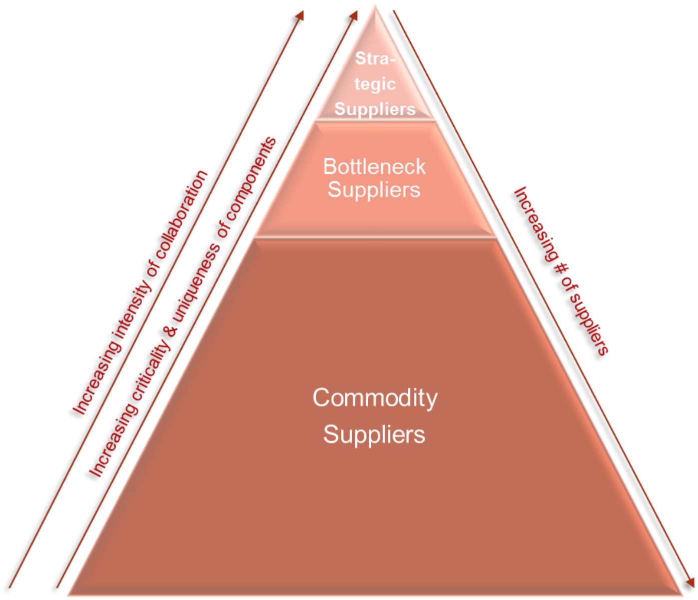

Figure 8: Stratification of supplier base by OEMs in MA

The actual number of supplier firms that are considered truly critical or strategic is small; they account for only 10% to 15% of the OEMs' supply base (composed of around 1,000 firms), and sometimes considerably fewer. Interviews revealed that these strategic suppliers are not necessarily SMEs – often, they are other multi-national companies (MNCs). It seems that small suppliers are often considered "strategic" when they make parts and components that must meet particularly stringent quality and reliability requirements or that are difficult to manufacture. By contrast, MNC's are more likely to be considered "strategic" if they supply a key technology.

Large OEMs are engaged in significant "**new product Introductions**" in Massachusetts—as such, they require rapid and on-time delivery of critical parts and parts needed to ramp up production. OEMs are more likely to use in-state suppliers when labor is not a key cost driver and price is not the primary consideration in sourcing.

> *"Time trumps costs when it comes to developing a new product."*
>
> — OEM in Consumer Affairs

These changes have significant implications in terms of what it takes to be a "world-class supplier," where "world class" is increasingly the standard for suppliers today. Regardless of industry, OEMs today have similar expectations of their suppliers. Several criteria are seen as standard requirements for top suppliers:

- Standard certifications (e.g., ISO, AS)
- Technical skills (IT, CAD/CAM)
- Zero defects in shipped product
- 100% on-time delivery

- Truly "lean" practices
- "Nimbleness and curiosity"—in other words, a mindset of openness to new challenges
- Regular (usually yearly) price reductions
- Commitment by the SME, at the level of the CEO, to communicate directly with the OEM
- Transparency as to cost drivers

"Zero defects" is of course the gold standard in manufacturing. It is also often challenging for small firms to achieve without assistance to improve their manufacturing processes. The issue is not only one of (sometimes unsatisfactory) objective performance, but also one of "mentality": though size itself is not always a guide to performance. Small firms sometimes lack the attitude that subpar performance on these metrics is simply unacceptable under any circumstances.[8]

OEMs are conscious that suppliers need to make a sufficient margin of profit to be able to re-invest; thus, starving suppliers is ultimately self-defeating. "Detroit" and historically harsh practices with suppliers within the automotive industry were repeatedly mentioned as a cautionary example. At the same time, OEMs have a basic expectation that suppliers will offer regular price reductions, especially since purchasing managers are assessed on the basis of their ability to drive annual cost reductions. Many OEMs are themselves exposed to fierce price competition. Also, annual cost reductions are seen as a leading indicator of the supplier firm's ability to engage in process improvements and remain competitive.

OEM managers we spoke to generally believe that the way out of this contradiction between ensuring sufficient margins for suppliers and achieving expected price/cost reductions, is through the adoption of lean practices—not only within supplier firms but, ideally, throughout the supply chain such that the entire system is lean (not just individual nodes in the chain). Several OEMs singled out the importance of deep collaboration between the supplier's engineering teams, the OEM, and the OEM's customer in the design of final products and the components that go into them. Managers saw collaboration as one of the surest ways to achieve sustainable cost reductions. In practice, however, this is very difficult, for several reasons:

- Even at the firm level, **"lean"** is less a set of discrete practices that can be taught, learned, and implemented like algebra, than it is **a culture and a never-ending journey**. Achieving and consistently acting on this culture places very high requirements on management and workers. While the importance of lean practices is universally acknowledged, OEMs felt that true "leanness" was rarely achieved.
- Making the supply chain as a system truly lean requires **high levels of trust** between the OEM and the supplier, an awareness of the potential benefits, and a readiness to invest time and effort. Specifically, it requires that OEMs and suppliers open their books to each other, to identify where the main cost drivers lie so that these drivers may be eliminated.[9]

[8] One OEM representative emphasized that the zero defect requirement made his company "skittish" about dealing with small suppliers but he also noted that he had had very positive experiences sourcing from some very small companies.
[9] This level of trust is often lacking. One OEM representative noted that the SME suppliers themselves sometimes preferred more distant, arms-length transactional relations, rather than close cooperation and partnership.

- Investing the necessary time in a supplier-OEM relationship can be difficult, especially when the size difference between the two is substantial. Small suppliers complain about **lack of access to OEM decision-makers**.
- Ultimately, company officers are responsive to the parameters they get measured and assessed on. The criteria used to assess their performance are often if not always quantitative ones. Subjective or **qualitative criteria are rarely taken into account**.[10]

In practice, while most OEMs agree that, ideally, supply chain relations should be structured as deeply cooperative partnerships, they also note that this ideal is achieved in no more than a handful of supplier-OEM relationships. What OEMs expect from new suppliers are innovative components that both add value to the OEMs' products and support the OEMs' product innovation process.

On the other hand, OEMs also have to make certain commitments to suppliers to ensure a sustainable and long-lasting relationship. Besides supplier development initiatives, OEMs can make several important contributions:

- *Communication:* For example, sharing product and business road maps with SMEs so they understand OEM pressures and trajectories
- *Long-term contracts:* Long-term contracts give suppliers, especially small suppliers, the certainty needed to develop strategic plans for investing in machinery, personnel, and training.
- *Direct and indirect financial support:* Banks are cautious about lending to SMEs without a solid order record and business plans that include long-term contracts. OEMs can assist in this area by acting as guarantors for loans and credits.
- *Business opportunities for national and international expansion:* High-performing SMEs are eager to expand their business but may be limited in terms of their financial and managerial resources. For this reason, most SMEs are looking for opportunities to serve existing customers even when they relocate abroad.

Clearly, the relationship between OEMs and SMEs is evolving toward higher standards *and* increased collaboration. Many OEMs are "taking the high road" in terms of investing in their suppliers to help them be more productive and potentially grow. The goal for Massachusetts is for all OEMs that work with suppliers to take this approach.

Responding to significant changes within the supply chain, many OEMs have created supplier development initiatives for the supplier firms with which they want to develop a long-term relationship. Commonly, these initiatives involve some combination of the following practices:

- Sending engineers or other technical staff (e.g. Six Sigma specialists) to suppliers to help with specific operational shortcomings and lean practices.
- Guaranteeing work and/or helping broker credit lines to allow suppliers to purchase new equipment.

[10] One OEM representative noted that measuring a "relationship" is difficult; this in turn complicates the task of getting OEM staff to pay proper attention to these issues.

- Supporting suppliers when they follow the OEM abroad, and ensuring the supplier's market share in those new countries.
- Helping suppliers manage their own supply chain.
- Helping suppliers assess their own state of readiness for further development.[11]

At present, OEMs carry out these activities largely independently, though there are a few cases where third-party entities—specifically MassMEP—have been engaged to coordinate workforce and lean training programs for local SMEs.

A good example of collaboration between OEMs is the "Accelerate Program" started by the Wisconsin MEP. In this program, which ran from 2005 to 2010, OEMs worked with select suppliers and MEP on lean management and process improvement matters with a particular focus on reducing the manufacturing critical-path time, i.e., the typical amount of calendar time from customer order creation to delivery. More than 400 projects with 28 OEMs in 25 states were completed over 7 years. [31] Participating companies were highly satisfied with the results since the program improved key metrics like manufacturing critical-path time, quality, inventory, and overall production-related costs [32].

5.3 SMEs within the Manufacturing Innovation Ecosystem

As noted earlier, 97% of all manufacturing establishments in Massachusetts are small or medium sized. Machine shops account for a significant number of these manufacturing SMEs (see Figure 14 in the appendix); typically, they perform contract manufacturing and work within regional, national or international supply chains.

The SME landscape in Massachusetts includes four different types of businesses. These are classified according to company life-cycle and type of product architecture, as depicted in Figure 9. Along the horizontal axis, the figure distinguishes between newly founded and incumbent SMEs; along the vertical axis, the distinction is between SMEs that produce parts and components and SMEs that make end products.

[11] Suppliers' readiness to ramp up production emerged as a particular point of concern in interviews with several OEMs.

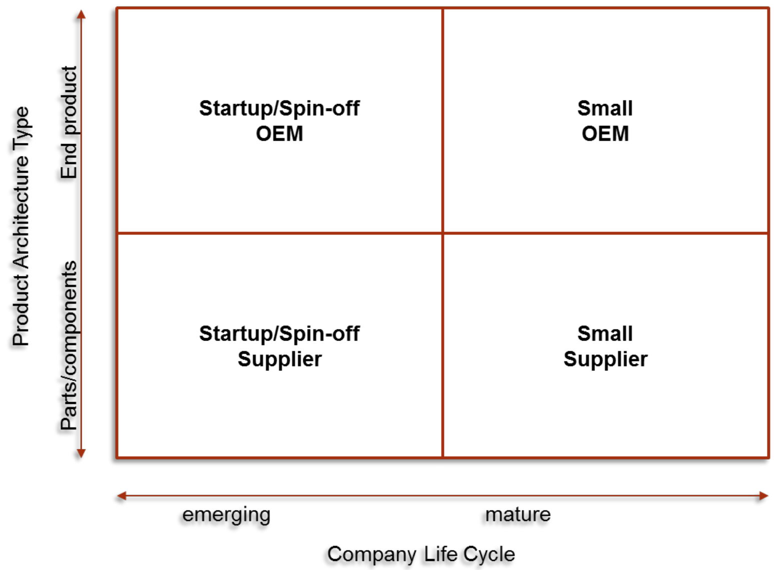

Figure 9: Classification of SMEs

Startup or spin-off suppliers produce less complex parts and components and seek to engage with large OEMs to sell their products. In terms of life cycle, high-performing startup or spin-off suppliers are on a path to grow to mature small suppliers (the fourth quadrant in the figure) and ultimately to become strategic suppliers (see Figure 8).

Small suppliers normally start as emerging startup or spin-off suppliers and grow to become part of OEM supply chains for precision parts. The large number of machine shops in Massachusetts fit into this category. Machine shops are not positioned to become strategic partners because they are engaged in high-precision, made-to-order manufacturing of less complex parts and do not have proprietary products. For these suppliers, support to improve process efficiency with initiatives like lean manufacturing or Six Sigma is essential.

Startup or spin-off OEMs produce more complex, proprietary products that can be marketed by the OEM or as part of a larger system. The pathway for these kinds of SMEs is to grow through new customers and markets into a mature small OEM and ultimately to become a large OEM.

Small OEMs, which have their own product portfolio, seek to enter new markets and connect with other OEMs. These companies are also often well positioned to partner with universities.

We interviewed several small suppliers and small OEMs that could be considered high performing, or on the way to becoming high performing, for this study. A number of precision engineering firms (referred to more generally as machine shops) were included in this group. As noted previously, these SMEs often enable new product introductions and undertake prototyping activities for OEMs based in the region. They also play important roles as providers of key equipment and strategic parts for OEMs' physical production systems within the state.

Several existing and potential pathways are available to increase the innovation capacity of SMEs in the state.

Despite growing cost pressures and increasing consolidation within OEM supply chains, Massachusetts SMEs are not only in a good position to take advantage of heightened interest in innovation and shorter lead times, they may also be buoyed by trends that are making manufacturing in the U.S. more attractive generally. OEM interest in greater collaboration also creates new opportunities to build long-term relationships.

In addition, the relatively diverse manufacturing-related key sectors of the Massachusetts economy that rely on the state's "manufacturing backbone" (see Section 4.2) provide a diverse customer base for SMEs. The ability to supply across sectors helps SMEs in terms of business cycles, cross-selling, and also cross-fertilization with respect to learning and best practices.

Strong institutional support is available in Massachusetts for process improvements and workforce training to help SMEs produce more efficiently. Section 6 provides an overview of available support mechanisms.

In terms of challenges within the innovation ecosystem, a primary challenge for SMEs is that they are **not easily integrated** into structures for learning about and participating in the development of new products and processes, including frontier technologies. Access to this knowledge, whether from OEMs or universities or other third parties, is limited. In particular, despite some pilot efforts within the state, SME relationships with universities are weak. In interviews, SME managers repeatedly stated that many universities are not "user-friendly" places—that is, they are frequently hard to navigate.

Weak linkages with startups are a further challenge for SMEs. Improving these linkages could open new market opportunities, especially since the vibrant startup community in the greater Boston area needs manufacturing services that could be delivered by small suppliers such as machine shops.

5.4 Universities and Research Institutes in the Manufacturing Innovation Ecosystem

Much has been written about the important role universities play in fostering innovation and generating economic development benefits for the regional economies in which they operate. One of the obvious advantages of a university to the ecosystem is that, "unlike so many participants in the local economy, they are immobile" [33].

Massachusetts universities in particular have an enormous impact on the region's economy: throughout the state, about 500,000 students are enrolled in more than 100 institutions of higher education and billions of dollars go to support world-class basic and applied research at these institutions. Entrepreneurial activities on university and college campuses have led to the founding of many innovative startup firms.

In addition to all the tangible outcomes they generate, universities also create many positive externalities for surrounding communities [34] and play at least two important roles that can help foster regional economic development. First, universities create a “space for open-ended conversations about industry development pathways and new technological and market opportunities." They also "increase the local capacity for scientific and technological problem-solving" through the flow of ideas from startups, joint research with companies, consulting, and the hiring of students. [33]

Advanced manufacturing in Massachusetts has benefited from all of these innovation externalities associated with local universities and colleges. In particular, the state’s universities boast top research labs and centers (often supported in part by state and federal funding) that are developing the next generation of advanced manufacturing technologies. Examples include the recently launched Raytheon-UMass Lowell Research Institute, which is focused on flexible and printed electronics and the Novartis-MIT Center for Continuous Manufacturing, which focuses on biomanufacturing. Both of these centers are sponsored by large OEMs and support basic and applied R&D. Other centers build on regional strengths in areas such as robotics (e.g., the Wood Hole Oceanographic Institution Center for Marine Robotics and the UMass Lowell New England Robotics Validation and Experimentation Center or NERVE), advanced materials (e.g., the MassNanoTech Institute at UMass Amherst, the Northeastern Nanoscale Technology and Manufacturing Research Center, and MIT.Nano), life sciences (e.g., the MIT Medical Electronic Device Realization Center or MEDRC and the UMass Lowell Biomanufacturing Center), defense-related research (e.g., Draper Labs and the U.S. Army Soldier Research, Development and Engineering Center), and advanced manufacturing technologies more generally (e.g., the Advanced Technology and Manufacturing Center at UMass Dartmouth, the Lab for Manufacturing and Productivity at MIT, and the Fraunhofer Center for Manufacturing Innovation at Boston University). Some centers, like the UMass Dartmouth Massachusetts Accelerator for Biomanufacturing, are designed specifically to work with startups that can benefit from the use of shared facilities.

Clearly, universities are already a critical part of the state’s manufacturing innovation ecosystem. Moreover, they are positioned to play an even greater role going forward given the current focus on emerging technologies and industries that are important to the Massachusetts economy.

We identified at least two areas of opportunity for universities in the state’s advanced manufacturing innovation ecosystem.

Despite flat or declining public funding for basic research in recent years [35], advanced manufacturing has attracted significant national attention and investment. The creation of a **National Network for Manufacturing Innovation** (NNMI) [36], which proposes to create at least 15 Institutes for Manufacturing Innovation (IMI) around the country, is arguably one of the most important science and technology initiatives put forth by the federal government in recent years. This effort recognizes the importance of manufacturing to the country’s innovation capacity and is based in part on the German Fraunhofer Institute model and the applied research model of public/private, university and large/small company collaborations (see Section 5.6).

Massachusetts universities have submitted bids in response to NNMI last calls for proposals and will no doubt be included in future bids, given the range of expertise that exists in the state. While the hope is that Massachusetts will host at least one IMI, the extensive work and initial collaborations that have been prompted by the **NNMI process** will yield benefits even if no Massachusetts institution is successful in the national competition. Those involved with this process should convene to discuss what aspects of individual bids could be implemented at the state level, potentially building synergies across bids.

The NNMI process could also be helpful in terms of developing advanced manufacturing technology road maps for the region. Such road maps would identify advanced manufacturing technologies of particular importance to the state's leading industry clusters and develop ideas for how best to support and advance research in these areas.

Another area of opportunity for strengthening the manufacturing innovation ecosystem involves increasing the **engagement between universities and SMEs.** While there have been some successful examples and pilots (see case study below), some fundamental obstacles exist that make such collaborations challenging.

First, SMEs face organizational challenges when working with universities. As already noted, SMEs report that they find universities hard to navigate and not user-friendly. Second, universities and SMEs have different objectives and agendas. Academics see innovation as "something that is radically new deriving from newly created knowledge" while SMEs see innovation as creating a product or process that will increase the firm's profits [37]. Third, SMEs are usually working under short- or medium-term time constraints. Universities work with longer timeframes. Finally and perhaps most importantly, the costs of collaboration can be prohibitive unless funding is provided by the SME or a third party.

Case Study

A Massachusetts paper mill facing changes in the market place and changes in people's use of paper, (a shift towards electronic documents), engaged in a collaboration with the Process Development Center at the University of Maine in order to develop new grades of highly specialized papers for the specific end users. It is now specialized in customized manufacturing of small-batch high-quality specialty papers. With limited resources, the company focused more on agility and responsiveness and was able to offer prototyping space at the company to university researchers. As opposed to larger mills, the Massachusetts paper mill's flexibility was a key value proposition for researchers that often struggle to find real-world testing conditions for their inventions. The SME, in turn, is able to foresee and train on the upcoming products being developed at the research center. This shift to a more innovative and responsive strategy for the company was due primarily to the strong support by the company's top management, which insisted on finding a university partner with a strong technological fit and has a strong appreciation of the current R&D projects. It is apparent that a clear win-win situation for both parties (innovation support by universities on the one hand and real-world testing environment on the other) is essential to foster collaboration between the two.

Finding ways to engage SMEs in research and discussions about new technologies is crucial to increasing their innovation capacity. One way to engage SMEs in university collaborations is through competitive grants, like those offered by the Small Business Technology Transfer (STTR) program. Facilitating and broadening SME-centered industry-university collaborations offers another promising path for increasing innovation capacity among SMEs [38]. In Section 5.6, we discuss the German model of research consortia, which could be instructive for Massachusetts.

5.5 Startups in the Manufacturing Innovation Ecosystem

Massachusetts is widely regarded as one of the most innovative and entrepreneurial states in the country.[12] Innovative startups, which may grow out of universities or out of larger established firms, are at the heart of the state's innovation ecosystem.

What is less well known is the extent to which these startups are engaged in advanced manufacturing processes. Research on startups based on technology developed at MIT and licensed through the MIT Technology Licensing Office (TLO) found that approximately 80% of all TLO startups founded between 1997 and 2008 required some kind of production-related capabilities [39].[13] In addition, a study of Massachusetts firms that are receiving federal Small Business Innovation Research (SBIR) grants found that at least 15% (or 500 firms) that received grants between 2009 and 2013 were engaged in advanced manufacturing processes. These grants accounted for approximately $200 million of the $1.2 billion total that Massachusetts firms received in SBIR grants over this time period.[14]

Given the region's strong and growing engineering capabilities and the trend toward combining hardware and software to form "hybrid" technologies (in consumer and medical devices, for example), startups have become an increasingly important source of manufacturing innovation. The emergence of startup incubators/seed funds such as Bolt that focus on hardware companies reinforces the support system for such startups.

But startups also face challenges in the scale-up phase. Growing innovative companies is a subject that is increasingly drawing attention, both in the United States and globally, as regions and countries focus on reaping some of the downstream benefits of their startup ecosystems. [40] The scale-up process is particularly challenging for startups engaged in the production of complex production-oriented technologies (as opposed to software). Such technologies often require larger amounts of capital and longer time horizons (often over ten years) to demonstrate their viability at commercial scale. [39]

[12] The Milken Institute's State Technology and Science Index 2014 as well as the ITIF's 2014 State New Economy Index rank Massachusetts as number one. The former analyzes technology and science capabilities of each U.S. state alongside their success at transforming those capabilities into companies [60]. The latter evaluates states' fundamental capacities in the "new economy "in terms of knowledge jobs, globalization, economic dynamism, digital economy, and innovation capacity" [59].
[13] Generally speaking, firms that license technology through the TLO are less likely to be software-related.
[14] In terms of total SBIR and STTR grants, Massachusetts is the second most successful state in the country behind California (see Figure 13 in the appendix) and is the leading state in the country in terms of SBIR/STTR grants per capita (see Figure 14 in the appendix).

There are several points in the early stages of this process where actively engaging with the manufacturing innovation ecosystem could help startups achieve scale and, importantly, facilitate scale-up in the Commonwealth.

First, startup technology companies often have a promising idea for a new product but lack the skills to manufacture it. **Early-stage prototyping**, which requires multiple iterations that can take several months or several years, often requires close proximity between the startup and its suppliers so that the latter can respond to changes quickly while still providing high quality. Massachusetts, with its extensive network of high-precision machine shops and experience in new product introductions, provides competitive advantages to startups at this stage of development.

However, connections between the innovative startup community and the state's high-precision machine shops are weak, with few formal or systematic forms of interaction. One manager of a startup suggested that companies in the greater Boston area are potentially as likely to connect with suppliers in California or China as they are to connect with suppliers in Massachusetts. Thus, it will be important to underscore the region's capabilities in prototyping and early-stage piloting and open better channels of communication between these communities.

A recent pilot with Greentown Labs, an incubator for clean energy companies, exemplifies a first step in this process. Whether the state can also position itself to support scale-up beyond pilots remains to be seen. Recently, companies have been more likely to go abroad to lower-cost locations for commercial scale-up.

A second area of opportunity for supporting the scale-up process in the region is with **potential customers.** Early adopters are among the most important factors that can help a startup "cross the chasm" in the early stages of scale-up [41]. Customers or potential customers who are willing to partner during beta testing of a new product are critical. Increasingly, strategic partners have been playing this role in the United States. Such partners, which are usually large companies (including OEMs), are becoming more engaged in startups through equity investments and other arrangements [42] in which they provide not only capital but capabilities and know-how in exchange for the exposure and experience they gain from the startup. This is particularly important for startups that, because of their longer development horizons and higher capital needs, do not necessarily fit well with a venture capital funding model. Given the diversity and sophistication of OEMs in Massachusetts, a more systematic effort could be made to connect startups and OEMs. This would benefit both parties as well as the regional economy. Introducing large potential customers to startups is the goal of several initiatives that are already in place (e.g., the NECEC Strategic Partners program and Fintech Sandbox's efforts to provide scrubbed financial data from large financial services firms to financial services startups for beta testing). More could be done in this area, particularly with respect to advanced manufacturing companies, where the scale-up process can be more challenging due to capital requirements and longer time horizons.

This review of the four key nodes in the manufacturing innovation ecosystem – OEMs, SMEs, universities, and startups – highlights the multiple ways these actors coexist within the same regional innovation ecosystem, often working closely together, but in some cases missing opportunities for greater collaboration and greater overall enhancement of the region's innovation capacity.

5.6 Case Study: Increasing Innovation Capacity in German SMEs

Germany provides an interesting case study for the U.S. with respect to strengthening SMEs in the manufacturing industry. Despite Germany's relatively high labor costs, 19% of all employees work in manufacturing [43]. German "Mittelstand"[15] companies, in particular, have been highly successful in global manufacturing markets. In terms of overall manufacturing output, Germany ranks fourth in the world [44]. German approaches to innovation, upgrading and training/apprenticeships have often served as models for other countries (see e.g. [3]). We chose Germany as a useful case study for Massachusetts because of Germany's success with building a strong SME manufacturing base.

The presence of the Fraunhofer Institutes, which act as a bridge between research universities and industry, is a prominent and oft-cited factor. The Fraunhofer Society, headquartered in Munich, is Europe's largest application-oriented research organization and comprises over 60 institutes across Germany, each of which focuses on a particular technology. Fraunhofer's mandate is to develop applicable technologies for industrial companies; this includes working with SMEs to bring cutting-edge technologies to market. [45] Numerous branches of Fraunhofer Institutes have been inaugurated around the globe, including in Boston.

Industry-university applied research is probably the most important mechanism for fostering innovation among manufacturers in Germany, particularly among SMEs. Germany has a long history of investing in applied research in areas where industry plays an important role. The German Federal Ministry for Education and Research ("BMBF") and the German Federal Ministry of Economic Affairs and Energy ("BMWi") have created several programs that focus on building innovation capacity among SMEs.[16]

Table 1 provides an overview of the most important initiatives and programs for funding applied research in Germany. Funding by BMWi is mainly through special programs and the German Federation of Industrial Research Associations (the German abbreviation is "AiF"). BMBF offers regular rounds of funding that are announced at random intervals with a clear technological focus. In addition, BMBF also starts special programs, like the Leading-Edge Cluster Initiative (see below), to support bigger projects in conjunction with the National High-Tech Strategy.

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[15] "Mittelstand" is a German term that has no precise corollary in English. It refers mainly to medium-sized private companies owned by families with a long tradition and a solid financial resource base that are successfully operating in the global market.
[16] In contrast to the U.S., companies in Germany and the E.U. are considered SME if they have fewer than 250 employees and annual revenues below €50 million.

Table 1: Overview of different applied research funding models in Germany

Type of Program	**Multilateral Consortium-based Research Projects**	**Bilateral Research Projects**	**SME Network Projects**	**Industry-oriented Research Projects**
Aim	Consortium-based joint development of pre-competitive product and process innovations	University-SME-based development of marketable prototypes of product innovations	Configuration of SME networks to jointly develop marketable product innovations	Making research findings accessible to SMEs to facilitate all kinds of innovations
Target Group	• Universities • Research Institutes (FhG, „An-Institutes“, etc.) • Large Companies • SMEs • Consultancies • Intermediaries	• Universities or research institutes • SMEs	• Universities or research institutes • SMEs (2+)	• Universities or research institutes • SME advisory board
Funding scheme	• 100% for Univ./RI • <50% for SMEs • Individual rate for large comp. (usually 20%)	• 100% for Univ./RI • <50% for SMEs	• 100% for Univ./RI • <50% for SMEs	• 100% for Univ./RI with mandatory SME participation
Funding body	• BMBF Standard Programs • BMBF Special Programs (Excellence Clusters, Research Campus, etc.) • BMWi Special Programs („Autonomik“, etc.)	• BMBF Standard Program „KMU-innovativ“* • BMWi – AiF ZIM SOLO • Ziel2 (2+ SMEs possible)	• BMWi – AiF ZIM KOOP **	• BMWi – AiF-IGF
BMBF: German Federal Ministry for Education and Research BMWi: German Federal Ministry for Economic Affairs and Energy AiF: German Federation of Industrial Research Associations ZIM: Central Innovation Program SME Ziel2: Regional development program of the EU for economically less-developed regions in Europe * to date: EUR 750M for 1,100 Projects ** in 2013: EUR 424M for 3,000 Projects				

The characteristics of these programs can be summarized briefly:

1. Multilateral Consortium-based Research Projects is a unique and important initiative to support the joint development of innovative products or processes between large OEMs, SMEs, universities, and applied research institutes (especially Fraunhofer). The participation of SMEs is mandatory. For universities and applied research institutes, funding covers all project-related expenses (personnel, hardware, etc.), while participating companies are reimbursed up to 50% of their costs depending on company size; in general SMEs receive up to 50%, large companies around 20%. This funding mechanism is also used for larger initiatives[17] and is discussed below in more detail.
2. The Bilateral Research Project Model supports collaborations between universities and SMEs to develop marketable prototypes using a funding scheme similar to Multilateral Consortium-based Research Projects.
3. The SME Network Project Model supports the formation of SME networks to jointly develop products. This model requires more than two SMEs and an intermediary that could be a university. Funding covers all costs of such universities and 50% of the costs of SMEs.

[17] The Leading-Edge Cluster initiative funds half of total project costs, with universities and applied research institutes reimbursed first at the 100% level, and companies reimbursed with remaining funds, usually less than 50% level.

4. Industry-oriented research projects are another unique model that funds universities to find ways to make research findings accessible to SMEs. SMEs participate on Industry Advisory Boards that meet at least twice during the project to discuss and steer the development of the research.

The multilateral consortium-based research project is the standard funding model of the German Federal Ministry for Education and Research. Research consortia are typically comprised of SMEs, universities, research institutes, large companies, consultancies, and intermediaries and focus on the development of pre-competitive product and process innovations.

Our research in Germany revealed two different kinds of consortium-based relationships that foster different types of innovation:

- The **value-chain based approach** where industrial partners represent adjacent tiers in the value chain with potential supplier-buyer relationships. This type of relationship is generally more likely to result in marketable products since a potential value chain with well-known supply chain structures is already in place. On the other hand, this approach seems to support more incremental innovations.
- The **complementary-competency based approach** brings together partners from different industries with different technologies to promote experimentation aimed at developing truly novel products and processes. In this model, there is a higher degree of uncertainty as to project results and more radical innovations are likely.

In both cases, the model is to enable innovation by bringing together partners who otherwise would not meet, particularly SMEs, who are central to the conversation that occurs with universities and large OEMs. Significant inter-firm communication with OEMs allows for first-hand knowledge exchange and mutual understanding of OEMs' future developments, technology road maps, and market opportunities. The model promotes faster development and wider diffusion of innovations that would otherwise emerge much more slowly and on the basis of bilateral cooperation, which reduces diffusion into the wider manufacturing ecosystem.

Based on fieldwork done in Germany, we identified several factors that determined the effectiveness of such projects in bringing innovations to market:

- **Consortium size,** with the ideal size being between three and five partners. Ideally the partners would include at least one participant from each category (SME, university or research institute, and large OEM).
- Close **alignment between the consortium's R&D objectives and participants' existing strategies.** Companies that are focused on a specific future technology (e.g., carbon fiber materials), are more likely to be committed to the project and to make significant contributions since success directly advances their interests.
- The nature of the research is **pre-competitive**. This prohibits any kind of favoritism in terms of funding companies' direct R&D activities. The research consortia focus on demonstrating the viability of technologies at the pre-prototyping stage, before any one company has taken on

greater risk with a particular product or technology. This is of particular concern in the medical device industry where the process of conducting clinical trials and gaining approval from regulatory authorities (such as the Food and Drug Administration in the U.S.) can take many more years.

Using the consortium funding model, Germany launched its Leading-Edge Cluster Initiative ("Spitzencluster-Wettbewerb") in 2008 as part of Germany's High-Tech Strategy to foster technology innovations deemed crucial to the global success of German industries. The initiative represents Germany's largest applied research funding program. Its objective is to support the formation and development of 15 regional technology/industry clusters. Each cluster receives €40 million worth of government funding over five years, plus at least a further €40 million in matching contributions from industry. Total funding for the program thus comes to at least € 1.2 billion over five years, or €80 million per cluster.

The initiative has taken a bottom-up approach to targeting specific research areas, with regions—led by the Fraunhofer Institutes, large OEMs, or universities—proposing different cluster/technology foci based on their distinctive regional capabilities. Current clusters include aerospace (Hamburg), medical devices (Nuremberg), smart manufacturing (Paderborn), software (Darmstadt), silicon (Dresden), biotech (Heidelberg), logistics (Dortmund), e-mobility (Stuttgart), and carbon (Munich).

Each cluster consists of several dozen multilateral consortium-based research projects with between a handful and several dozen participating firms and research institutes. As stated above, each of these projects must involve significant SME participation. Each cluster must also have a professional management team; usually these have between 3 and 9 full-time positions. The clusters are chosen through a competitive application process and undergo repeated evaluations.

Each cluster must have an overall strategic research orientation, which the individual consortium-based research projects must directly contribute to. Both the larger strategic orientation and the R&D content of the individual projects are to be decided in a bottom-up process by the participating firms and research institutions themselves. While the research is pre-competitive and pre-prototype, there must be a clear and robust prospect of turning the research results into products with market potential within a relatively short time-span. Thus, the intention is that the participating firms play a central role in deciding the content of individual projects and the overall strategy. In practice, it seems that this works best in clusters where much of the research is already very applied and application-oriented. In clusters with a greater amount of basic research, universities and research institutes play a more important role in driving the organization of research activities.

Clusters within the Leading-Edge Cluster initiative have evolved in different ways based on several factors:

- *Industry structure.* Clusters with established pre-existing supply chains and strong focal companies tend to develop a center of gravity around the focal companies and are managed more entrepreneurially, whereas clusters that consist of a mere agglomeration of related companies without strong buyer-supplier relations tend to be more dispersed.
- *Technology.* Some technologies have the potential to completely transform an industry, whereas others merely improve on existing technologies. The latter tend to be driven by large OEMs that give SMEs the opportunity to participate in their value chain once the cluster initiative bears fruit. Transformative technologies, by contrast, tend to be driven by research universities and institutes and have the potential to generate new relationships, mainly based on the complementary-competency approach, in which no one company is necessarily dominant.
- *Company size.* Large OEMs can provide strong leadership with a higher degree of influence, whereas "Mittelstand" companies tend to encourage more decentralized coordination based mainly on informal pre-existing agreements.

Different clusters have developed different structures with regard to management and funding. Clusters with stronger leadership were more likely to implement unique, entrepreneurial approaches to management. For example, in some cases unsuccessful projects could be terminated by the steering committee. At least one cluster developed internal funding structures that provided funds for smaller, low-budget projects, especially for SMEs, to quickly assess the feasibility of cluster-related ideas and test the initial results of some cluster projects.

Our fieldwork identified several key factors for the success and effectiveness of individual clusters.[18] A clear vision, strategy, and overall goal against which all projects could be assessed seemed to be very important as it allowed steering committees to direct funds to relevant projects that added value to the cluster in general. In addition, close alignment of the cluster's R&D strategy with participants' business strategies is also critical. Absent this alignment, companies will work on projects reluctantly.

The presence of a driving force, like a large OEM, is very helpful to generate momentum and buy-in and sustain the cluster; thus, leadership needs to be part of cluster management. The management team also needs to be able to adapt to potentially adverse developments, such as changes in regional industry demographics or shifting technological preferences in the relevant industry.

The regional proximity that comes with Germany's cluster model facilitates collaboration among partners, but is not a sufficient factor for ensuring success. Technological expertise is far more important, although physical proximity does help the cluster gain more attention from companies in the region.

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[18] Some of these success factors are also mentioned in a report by the RWI Institute that evaluated Germany's Cluster Initiative (for more details see [20]).

Thus far, output from Germany's cluster initiative has been impressive. After seven years, the 15 clusters in the Leading Edge Cluster initiative have been able to quantify and report several key outcomes [46]:

- 900 innovations,
- 300 patents,
- 450 (PhD) dissertations,
- 1,000 Bachelor and Master theses, and
- 40 startups.

The initiative also increased SME investment in R&D, leveraging €1.36 of SME spending for every euro of public spending. [46] While data on the wider contributions to the economy of the Leading-Edge Cluster initiative has not been published, one cluster manager we interviewed disclosed that his cluster had, within the first two years of its existence alone, created so many new jobs that the increased payroll tax almost made up the entire state funding the cluster had received.

In sum, the success of clusters is determined by the interplay of the factors mentioned above. A clear vision and strategy, paired with an influential nucleus of core institutions, is among the unique characteristics of the German cluster model. Other factors, including a high degree of innovation potential, common activities within the cluster, regional proximity, nimbleness, and adaptability, are also important.

6 The Intermediary Landscape

Massachusetts is rich in intermediary organizations that provide services and advice to SME manufacturers throughout the state. Table 2 and the discussion in this section summarize the six primary types of assistance provided by these intermediaries.

Table 2: Available support for manufacturing SMEs in MA

Issue Area	Types of Institutional Support Services	Examples of MA Service Providers/Programs
Process Improvements	• Lean Manufacturing • Quality Assurance Controls • Certifications • Technical/Engineering Support Services	• MassMEP • Greater Boston Manufacturing Partnership • Regional Employment Boards • Workforce Training Fund
Workforce Training	• Training • Curriculum development • Student engagement and outreach	• Regional Employment Boards • Workforce Training Fund • MassMEP/MACWIC • PMRAP Initiative/Machine Tooling Assoc.
Strategic Technology Development	• Brokering University-Firm Links • Identification of future technologies & build clusters • Subsidies for research collaborations • Encouragement of SME/supplier participation in OEM-University research consortia	• University research centers (mainly OEMs, startups) • PMRAP "PFI" program (expired) • Mass Tech Collab. Research Matching Grants • Mass Dev. Manufacturing Futures Program
Technical and Engineering Process Support	• Engineering advisory support • Support adoption of new materials, processes etc. • Access to new equipment for prototyping, testing • Trial access to production software (CAD/CAM)	• PMRAP (expired) • MA Clean Energy Center, • New Mass "Manufacturing Futures Program" • University research centers (uptake may be difficult for SMEs)
Managerial & Professional Education and Advisory	• Advisory services (strategy, finance, operations) • Seminars and workshops for professional skills • CEO Mentoring	• MassMEP • AIM • Mentoring services in Universities (mainly focused on startups)
Marketing	• Market intelligence • Summits for OEMs-Suppliers matchmaking • Brokering new supply chains • State participation in major trade fairs	• MassMEP • PMRAP (expired) • Greentown Labs Initiative • MA Export Center • MA Procurement Technical Advice Center

1. Process Improvements

Process excellence allows suppliers to satisfy highly demanding OEM expectations with respect to speed, quality, reliability, and regular price reductions. Intermediary institutions help SMEs meet these requirements by providing and subsidizing various forms of workforce and lean training (including lean, Six Sigma, value stream mapping, kaizen, and training to attain various certifications). MassMEP has historically focused on providing training in continuous improvement as well as support for firms interested in attaining particular certifications (for example, MassMEP's "ISO Collaborative" allows firms to share the costs of certification). Training is also provided by the Greater Boston Manufacturing Partnership, a non-profit run out of UMass Boston. As discussed in Section 5.2 of this report, OEMs also provide process improvement training to select suppliers.

The state's Workforce Training Fund also provides financial support for firms to engage in training.

2. Workforce Training

Massachusetts firms, the state, and institutional intermediaries have devoted substantial resources and attention to workforce training, for both incumbent and "pipeline" workers. The Workforce Training Fund is the best-known program; in the manufacturing industry it has predominantly benefited machine shops (see Figure 16 in the appendix) and has mainly focused on training in lean practices (see Figure 17 and Figure 18 in the appendix).

In addition to public and private training providers, numerous regional consortia and initiatives have been formed to better coordinate the design and provision of training among firms. Vocational technical high schools, community colleges, and other intermediary institutions have also developed novel training certification schemes, like "stackable" credits.

Important examples of these consortia are the Precision Manufacturing Regional Alliance Program (PMRAP) and the previously discussed MACWIC program. MassMEP together with regional employment/workforce investment boards have often played a key role in developing and coordinating these initiatives, as have industry bodies like the Western Massachusetts Section of the National Tooling and Machining Association. Further, more specialized training is offered by some university or public research centers (e.g., the Massachusetts Clean Energy Center offers wind-turbine-related training).

3. Technical and Engineering Process Support

Process excellence is partly about management skills and organizational culture (like lean), but it also has a significant technical and engineering dimension. Meeting OEM expectations requires high levels of production skills. Beyond OEM expectations, the increasing speed of technological change and the introduction of new production technologies (e.g., additive manufacturing) poses particular challenges to SMEs, who have to try to keep abreast of the possibilities and threats posed by technology changes.

Technical and engineering process support can take the form of engineering advice to (1) optimize production processes and better serve customer needs, (2) low-cost access to manufacturing equipment and associated technical support for prototyping, testing and demonstration, (3) access to a broad portfolio of software systems, (4) information about new materials, processes, and tools, and technical support to facilitate their adoption.

It appears that services of this kind are underprovided in Massachusetts. Numerous university research centers and institutes possess certain pieces of equipment and provide access to some of them, usually for a fee (an example is the 3-D printing equipment at UMass Lowell's NERVE Center). However, accessing university resources is often not easy for SMEs (see discussion in Section 5.4), and university purchasing decisions are usually driven primarily by research needs, which may well diverge from the requirements of firms trying to develop a new product.

Also, access to equipment at universities and research centers is at present highly fragmented—there is no central registry where firms can look up what equipment is available where. Some facilities in the Commonwealth have specialized equipment, for example, the Massachusetts Clean Energy Center possesses dedicated prototyping and testing facilities for wind turbines, blades, and materials and a similar center for marine robotics is now being built at Woods Hole Oceanographic Institution.

The PMRAP initiative included a year-long engineering support service, in the form of an industrial engineer who was available to participating firms. Surveys of firms conducted as part of PMRAP revealed that many precision machinists possessed only antiquated or incomplete CAD/CAM software. Over the two years that PMRAP operated it produced valuable insights into how SMEs do or do not upgrade their capabilities.

Recently, a new program supported by MassDevelopment began providing funding to SMEs (in amounts up to $75,000) to help them access "innovation centers" for assistance in solving "complicated technical problems." This pilot project is engaging three private and non-profit centers in Massachusetts and one center in Connecticut to act as partners to SMEs that are looking to upgrade their technological capabilities.

4. Strategic Technology Development

Beyond the challenges suppliers face in accessing and absorbing the scientific and technological expertise needed to improve their products, the regional industrial ecosystem as a whole faces the wider challenge of identifying and supporting emerging technologies in areas where Massachusetts possesses potentially unique strengths and capabilities.

At present, the Commonwealth sponsors research and cluster development efforts through the MassTech Collaborative and its Innovation Institute, which engages with stakeholders to identify promising emerging technologies and actively builds constituencies around supporting greater investment and activity in those areas. The Collaborative Research Matching Grant Program provides up to $5 million to match private investments in technologies/industries that are considered promising for the state's economic growth. Recent investments related to advanced manufacturing include the Raytheon-UMass Lowell Research Institute, which is focused on flexible electronics, and the Woods Hole Oceanographic Institution Center for Marine Robotics.

In addition, several private non-profit organizations help develop strategic plans and provide support to advanced manufacturing industries. The Mass Tech Leadership Council works with industry leaders to develop analyses, strategic plans, and working groups to support some of the state's most promising tech-related industries (robotics, for example). Other trade associations, such as trade associations for medical devices or biopharma, may directly or indirectly address manufacturing-related issues.

5. Managerial & Professional Education

In interviews, OEM managers emphasized that beyond technical capabilities, they also look for certain attitudinal qualities in suppliers— in particular a “culture of curiosity” that makes SMEs eager to solve problems. Conversely, SME executives we interviewed (both in Massachusetts and in Germany) emphasized the value of close communications with OEMs (their customers) to help them understand what OEMs are looking for and where they want to drive future technological development. From a different perspective, numerous interviews with intermediaries indicated that many of the problems local SMEs struggle with are more cultural than technological, especially the absence of developed managerial systems and strategic planning.

Problems associated with a lack of developed managerial systems and strategic planning at SMEs can be ameliorated through a combination of managerial and professional education and advisory and mentoring services. Events like the state’s annual “Advanced Manufacturing Summit,” where OEM executives have an opportunity to share their expectations and technology plans, can also help provide information on OEMs’ long-term visions for their supply chains.

MassMEP, Associated Industries of Massachusetts (AIM), and the Massachusetts Small Business Development Center Network offer diverse workshops and seminars for executives on topics such as leadership, strategy, finance, and business planning. There are also a variety of initiatives for mentoring executives (for instance AIM’s “CEO Roundtable”).

Overall, Massachusetts offers a solid system of support for manufacturing that has provided essential assistance to SMEs for more than two decades. However, given increasing pressures on manufacturers due to global competition, the Commonwealth needs to advance its efforts and maximize investments to support manufacturing in the state. In particular, the Commonwealth should take advantage of several high-level opportunities to shift emphasis and set long-term directions:

- The current system focuses on “point solutions” mainly in the areas of workforce training, lean practices, and certification. However, many SMEs have only a limited awareness of services and providers available in the state.

- The focus on lean manufacturing is necessary but not sufficient. More technological and engineering support is necessary to improve SMEs’ capacity for product and process innovation. Although some structures exist in Massachusetts to provide these services, they tend to be fragmented and are few and far between.

- Existing manufacturing support programs mainly focus on the supply side in the sense that they target suppliers and workers without, in many cases, a direct link to demand by OEMs (MACWIC is an exception to this). Few structures exist to systematically deepen OEM-SME collaborations.

- Massachusetts lacks a strategic vision for advanced manufacturing that looks out five to ten years in terms of changes in supply chains, technology road mapping, and talent and training needs. The system does a good job of responding to the needs of today and tomorrow. What is lacking is a collective vision of where the state will be in five to ten years in terms of advanced manufacturing and what its priorities should be in the long term with respect to technologies, training, and supplier development.

7. Summary of Findings

Massachusetts possesses a rich manufacturing innovation ecosystem—composed of large OEMs, SMEs, universities, and startups—that is supported by several effective intermediary organizations. Despite declines in manufacturing employment and in the number of manufacturing establishments, the state's manufacturing base remains highly robust in an increasingly competitive global economy. The Commonwealth's strengths in manufacturing—small-batch, high-quality, niche production of highly customized, high-knowledge early-stage products—play to the increased global focus on manufacturing innovation.

However, there are several weak connections between key nodes in the Massachusetts innovation ecosystem. In the face of increasing investments nationally and abroad that will strengthen competitors' manufacturing capabilities, the Commonwealth should look to strengthen these links.

In brief, SMEs in Massachusetts are relatively loosely linked to the innovation ecosystem. Supplier SMEs are highly dependent on OEMs when it comes to increasing their innovation capacity, yet there is often little communication between SMEs and OEMs. In addition, SMEs have difficulty connecting with universities. Their connection to startups, another key source of innovation within the ecosystem, is haphazard and ad-hoc.

By contrast, universities and research centers have strong relationships with large OEMs with whom they conduct basic and applied research. Universities and research centers are also an important source of innovation through technology transfer in the form of startups, many of which are engaged in advanced manufacturing.

OEMs have been making significant changes in the past five to ten years in terms of how they drive greater innovation in their operations, and specifically within their supply chains. This has led to greater consolidation, but has also increased OEM–supplier collaboration. "Commodity suppliers," like machine shops, make up a significant portion of the state's SMEs and play an important role in OEMs' innovation process by guaranteeing flexible and on-time delivery of high-quality parts. OEMs are the only organizations in the ecosystem that have strong bilateral relations to all the other parts of the ecosystem. They are critical to the ecosystem, but they operate primarily in isolation from each other.

Massachusetts has a rich institutional infrastructure that is already addressing some of the key issues facing manufacturers in the state (e.g., lean upgrading, workforce training, and certifications). However, the current system needs to move beyond these standard services. In addition, it remains largely focused on point solutions and on the supply side at present and could benefit from more engagement with

OEMs, an increased focus on product and process innovation, and a broader state strategy for advanced manufacturing.

8 Implications for Policy

Based on these findings, we identified four distinct areas of opportunity that offer high potential leverage to improve the Massachusetts manufacturing innovation ecosystem. The focus is on SMEs. Our ten recommendations are grouped under four headings: advanced manufacturing strategy and agenda, OEM collaboration, technological and managerial support, and connections between startups and the innovation ecosystem.

8.1 Advanced Manufacturing Strategy and Agenda

1. Develop an Advanced Manufacturing Strategy for the State

In contrast to the state's other cluster-focused strategies (e.g. for the biotech industry), advanced manufacturing requires the development of cross-cutting capabilities that work across industries (e.g. photonics, robotics, flexible electronics, and advanced materials). This makes it more challenging to develop strategies around particular capabilities. A deep understanding of advanced manufacturing capabilities, their importance within key clusters, and trends in technology as well as in the global manufacturing marketplace is required.

A robust analysis of the state's advanced manufacturing capabilities combined with engaging key manufacturing leaders in the state is necessary to develop an advanced manufacturing strategy and agenda for the next five to ten years. This includes involving relevant stakeholders and establishing appropriate governance structures to oversee such an effort.

2. Introduce Consortium-based Applied Research Projects

Grant funds should be used to encourage regional consortium-based projects including universities, OEMs, and SMEs that focus on pre-competitive product and process innovations, similar to the German model discussed earlier in this report. Previous and current experience with the federal Institutes for Manufacturing Innovation (IMIs) could be instructive in developing regional, project-based consortia.

8.2 Collaboration with OEMs to Drive Innovation and Upgrade SME Capabilities

3. Lead the Formation of a Commonwealth Manufacturing Innovation Advisory Group

OEMs are a driving force for innovation in Massachusetts, yet their collective voice on the subject is not being heard. With a window into global trends, R&D opportunities, supply chain demands, and training needs five to ten years out, OEMs need to be engaged in helping set the state's manufacturing innovation strategy going forward. Their participation should be coupled with the participation of several high-performing SMEs, and possibly others. A Manufacturing Innovation Advisory Group will promote long-term strategic thinking and collective action, and can highlight best practices for SMEs.

4. *Initiate an OEM Joint Supplier Upgrade Program*

Most OEMs have their own individual supplier development programs to help suppliers produce efficiently and meet the OEMs' delivery, cost, and quality requirements. There is little collaboration across OEMs in the same or different industries when it comes to upgrading the supplier base in the state, even when OEMs share similar suppliers.

Initiatives to upgrade supplier capabilities based on collaboration across OEMs from different industries could provide a robust mechanism for leveraging state resources, sharing best practices, and expanding support to SMEs. Such initiatives could focus not only on process and quality improvements but also on technical problem solving and workforce training.

5. *Introduce an Advanced Manufacturing SME Innovation Award*

While several awards for small businesses are already offered in Massachusetts, a state-wide award for innovative "world-class" advanced manufacturers would not only help set a high bar for SMEs and bring visibility to best practices for SMEs, it would also help change perceptions around advanced manufacturing in the state. The award could be given by a jury comprised of representatives from OEMs, universities, and intermediary organizations who are in a position to identify and evaluate particularly motivated and innovative SMEs.

8.3 Technological and Managerial Support for Innovation for SMEs

6. *Provide Technological and Engineering Support*

Thus far, state efforts to support SMEs have largely revolved around workforce training and lean practices. Such practices can lead to greater efficiency and accuracy in terms of quality, cost, and time. However, lean practices are a necessary but not sufficient requirement for success in today's global manufacturing environment. With the rise of new technologies, such as additive manufacturing, programs to support SMEs and build their innovative capacity need to go further. Specifically, support should be expanded to include centers, either existing or yet to be formed, that provide technological and engineering services to SMEs engaged in product and process innovation.

7. *Better Promote and Increase Awareness of Support Services for SMEs*

Although numerous support programs and intermediaries exist in Massachusetts, many SMEs we interviewed were not aware of the portfolio of manufacturing services available in the state. Multiple factors may account for this lack of awareness, but it speaks to the larger challenge of creating an ecosystem that is well connected and where knowledge flows freely. A coordinated communications effort among the various intermediaries that work in this area could help highlight and promote existing support programs and resources within the larger manufacturing ecosystem.

8. Support Education Programs for SME Executives

Advanced manufacturing SMEs are under constant pressure to improve efficiency and innovate. Being "world class" today requires not only a culture and practice of lean, but also sound managerial infrastructure and leadership, combined with a culture and practice of continual product and process innovation.

An executive education program offered by prestigious business and management schools in the state and focused on operations management would help SMEs rise to this challenge and meet a high bar for managerial excellence. Such a program could be offered on a competitive basis and could provide matching funds to support executive education for CEOs and managers at highly-motivated SMEs.

8.4 Connections between Startups and the Innovation Ecosystem

9. Better Promote and Connect SME Capabilities in Early-Stage Scale-Up to the Startup Community

Many Massachusetts startups, let alone startups outside Massachusetts, are unaware of the deep capabilities that exist within the state to support early-stage prototyping and piloting. Startups currently find manufacturing support through an ad-hoc, word-of-mouth process. Efforts by SME trade associations and intermediaries to better communicate these capabilities, together with a more explicit, systematic effort to connect SMEs and startups, is required.

10. Connect Startups with OEMs for Beta Testing and Piloting

In general, we found it difficult to assess the relative strength or weakness of current links between the Massachusetts startup community and large OEMs in the state. What is clear is that startups are almost always interested in stronger partnerships with potential customers and that more could be done to facilitate such partnerships within the region. Several efforts already exist in particular vertically integrated industries—such as, energy and financial services—but more explicit efforts could be geared toward advanced manufacturing-related technologies (e.g., robotics, advanced materials).

In summary, these ten system-level recommendations are intended to increase the innovation capacity of the Commonwealth's manufacturing ecosystem. Most of them are designed to strengthen links between key nodes within that ecosystem.

9 Conclusion

As this report has outlined, Massachusetts has significant assets and expertise in advanced manufacturing that have developed over decades, creating deep capabilities that help to drive innovation in some of the state's leading industry clusters.

But important changes are taking place—within companies and how they are organized for production, in terms of new "game-changing" technologies, and in the global economy as regions and countries work aggressively to increase manufacturing investments and build capabilities.

This changing landscape requires Massachusetts to "up its game" and look to maximize its manufacturing assets in terms of how the key nodes in the state's manufacturing innovation ecosystem are connected, how they collaborate within and across one another, and how innovation is supported and advanced within the system.

To meet the increasingly demanding standards for advanced manufacturing today, we need to set the region on a course of continual upgrading, particularly with respect to small and medium-size manufacturers. The course must also look ahead five to ten years to ensure we are building the capabilities, the technologies, the workforce and the collaborations that will help fully establish Massachusetts as a world leader in advanced manufacturing.

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11 Appendix

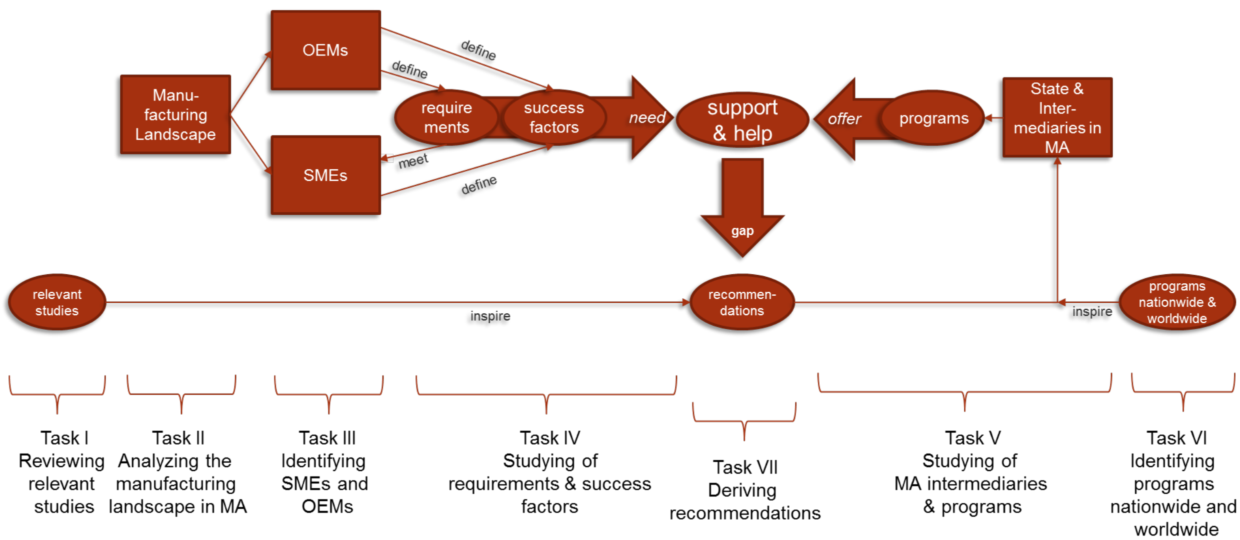

Figure 10: General methodology of the study

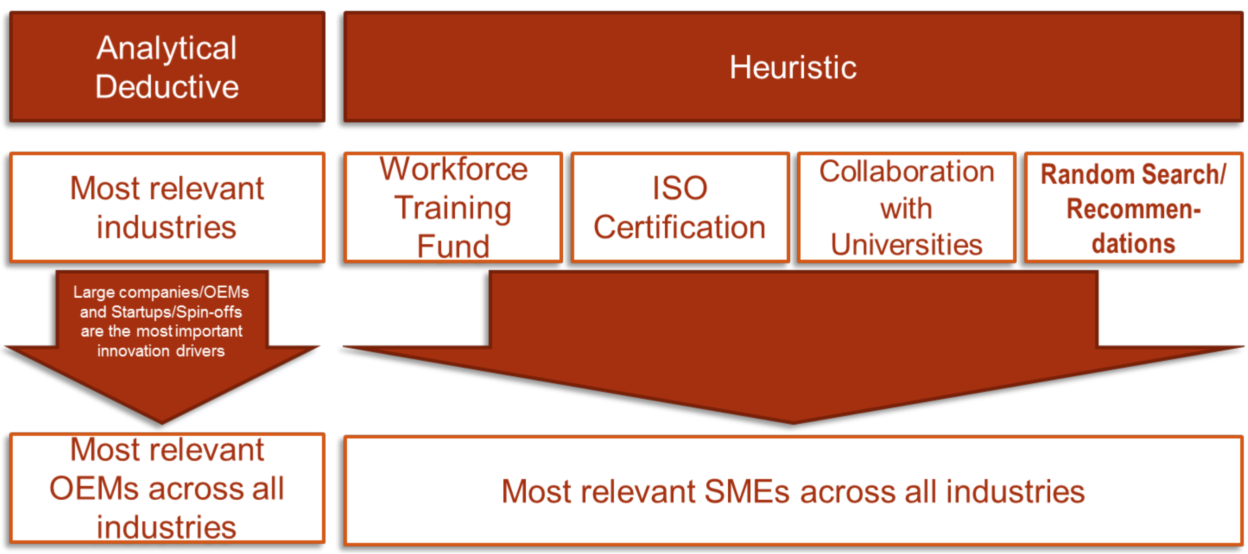

Figure 11: Methodology of the identification of interviewees

Table 3: Trends in advanced manufacturing in the United States and in Germany

	USA	Germany
Trends & develop-ments	Smart Manufacturing Systems [16] • Highly integrated smart systems provide pathways for competitively manufacturing materials and products • Agile processes in highly optimized manufacturing plants and supply networks enable rapid response to changes in customer demands • Ready access to manufacturing intelligence allow factories to run more efficiently and minimize use of resources • Products and processes are guaranteed safe and reliable through tracking of sustainable production and real-time handling • A manufacturing workforce with advanced skills and talent maximize the benefits of manufacturing intelligence • Smart processes minimize environmental impacts and improve sustainability of critical sectors	Industry 4.0 [15] • Horizontal integration through value networks • End-to-end digital integration of engineering across the entire value chain • Vertical integration and networked manufacturing systems
Fields of action	Industrial Community Modeling and Simulation Platforms for Smart Manufacturing • Create community platforms for the virtual plant enterprise • Develop next generation tool box of software and computing architectures for manufacturing decision-making • Integrate human factors and decisions into plant optimization software and user interfaces • Expand availability of energy decision tools for multiple industries and diverse skill levels Affordable Industrial Data Collection and Management Systems • Establish consistent, efficient data methods (standards) for all industries • Develop robust data collection frameworks (sensors) Enterprise-wide Integration: Business Systems, Manufacturing Plants, and Suppliers • Optimize supply chain performance through common reporting and rating methods • Develop open platform software and hardware to integrate and transfer data between SMEs OEMs • Integrate product and manufacturing process models Education and Training in Smart Manufacturing • Enhance education and training to build workforce for smart manufacturing	• Standardization and open standards for a reference architecture • Managing complex systems • Comprehensive broadband infrastructure • Human safety and data security • Work organization and design • Training and CPD • Regulatory framework • Resource efficiency

Table 4: Content analysis of relevant recent regional manufacturing studies

Study	Source	Year	Geogr. Focus			Study Objectives								Recommendations										
			local	regional	national	Opportunities/ Potentials Analysis	Analytic Industry Description	Success Factors	Needs	Concerns/Barriers/ Challenges	Growth/Economic Dvlpmt Strategies	Trends Analysis	Other	Workforce Training	Reduce Cost Disadvantages (tax, etc.)	Technical Assistance	Innovation Support/New Product Explor.	Busin. Opportunities (domestic & abroad)	Access to Capital	Image/Marketing	Collaboration	Innovation Ecosystem	Overall Strategy	Other
Advanced to Advantageous: The Case for New England's Manufacturing Revolution	[47]	2015		X		X	X		X	X	X			X				X		X	X			X
Accelerating U.S. Advanced Manufacturing	[18]	2014			X								X	X					X				X	X
Supply Chain Innovation: Strengthening America's Small Manufacturers	[19]	2015			X		X			X									X		X			X
MassMEP Survey Data Analysis	[48]	2014	X				X		X	X	X			X	X		X	X		X	X			
Berkshire Advanced Manufacturing Study	[49]	2013	X			X	X			X				X								X		X
Pioneer Valley Growth Business Study	[50]	2013	X			X	X	X	X															
Production in the Innovation Economy	[3]	2013			X		X			X		X	X	X			X				X	X		
Staying Power II: A Report Card on Manufacturing in Massachusetts 2012	[20]	2012		X		X	X		X	X		X		X					X					
Building Bridges to Growth: A Roadmap for Advanced Manufacturing in Massachusetts	[7]	2011		X		X			X					X	X	X	X	X	X	X				
Innovation-based Economic Development Strategy for Holyoke and the Pioneer Valley	[51]	2011	X			X	X	X		X	X			X								X		X
Reexamining advanced manufacturing in a net-worked world: Prospects for a resurgence in New England	[52]	2009		X		X	X		X	X	X													
Building for the Future: Foundations for a Springfield – Compre-hensive Growth Strategy	[53]	2009	X			X	X					X	X										X	
Precision Manufacturing Regional Alliance Project	[54]	2008	X				X		X				X											

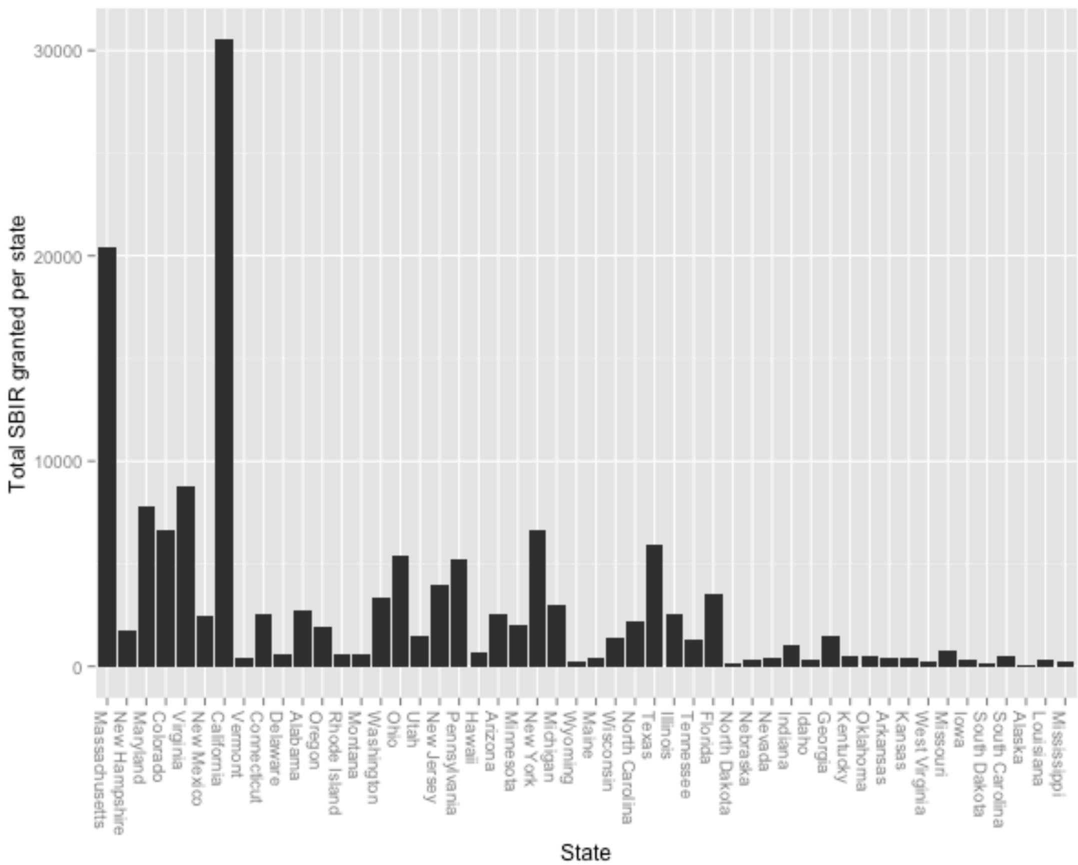

Figure 12: Total SBIR/STTR grants per state 2009-2013 [55] [56]

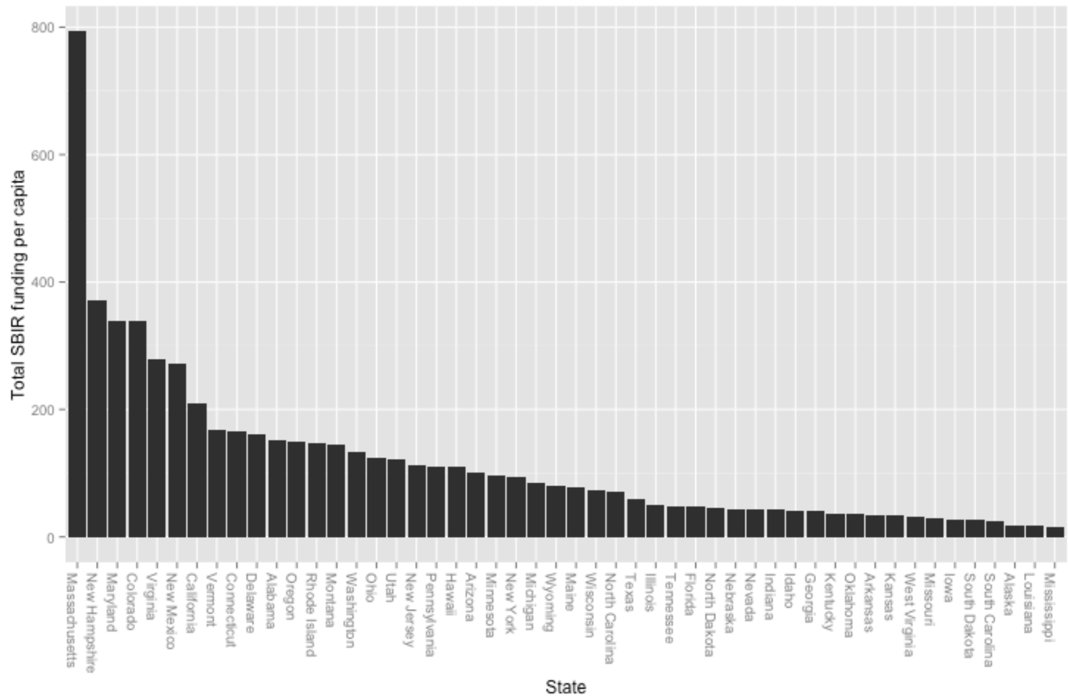

Figure 13: SBIR/STTR grants per capita per state in the U.S. 2009-2013 [55]

Table 5: Manufacturing subsectors on a 3-digit NAICS Code level

NAICS 31 - Manufacturing	NAICS 32 – Manufacturing	NAICS 33 – Manufacturing
Food Manufacturing	Wood Product Manufacturing	Primary Metal Manufacturing
Beverage and Tobacco Product Manufacturing	Paper Manufacturing	Fabricated Metal Product Manufacturing
Textile Mills	Printing and Related Support Activities	Machinery Manufacturing
Textile Product Mills	Petroleum and Coal Products Manufacturing	Computer and Electronic Product Manufacturing
Apparel Manufacturing	Chemical Manufacturing	Electrical Equipment, Appliance, and Component Manufacturing
Leather and Allied Product Manufacturing	Plastics and Rubber Products Manufacturing	Transportation Equipment Manufacturing
	Nonmetallic Mineral Product Manufacturing	Furniture and Related Product Manufacturing
		Miscellaneous Manufacturing

Table 6: Quantitative Analysis of Top 8 Manufacturing Subsectors

Sub Sector	Business Types	General Characteristics
Semi-conductors	• Manufacturing Service Provider • Supporting Process Service Provider (product development, customizing, etc.) • Manufacturing Machinery • Supporting Process Machinery (Testing, etc.) • Parts & components Manufacturers (packages, diodes, etc.) • Sellers & Distributors (Integrated Circuits, Semiconductors,etc.)	• 3% of all companies employ ~70% of all employees in this subsector • Large firms operate globally, SMEs operate regionally • Large firms offer same product range • Large firms & SMEs provide same main industries • (esp. Military/Defense, Automotive, Healthcare, Aerospace) • Some large firms are highly vertically integrated
Machine Shops	• Core Process Specialist (CNC milling, truning, etc.) • Multi Process Specialist (CAD, prototyping, manufacturing, quality assurance, etc.) • Industry Specialist (aerospace, etc.) • Parts Specialist (engine parts, etc.)	• Highest number of SMEs (~630 establishments) • Sales are moderate (Ø ~$1.7M per MS) • MS hardly grew over the last decade (currently Ø ~14 employee per MS) • MS serve the same industries (healthcare, industrial process variable, etc.) • MS are operating regionally with a regional customer base • MS have no proactive sales based on own products • MS have a diverse customer base • MS provide manufacturing services • A significant number of MS don't even have web sites (50%) and most others are not attractive • MS are numerous in nearly every other US state
Surgical and Medical Instruments	• Medical Instruments Mfg. (bronchoscopes, endoscopes, ophthalmoscopes, etc.) • Mfg. of Parts & Components for Medical Instruments (Electrode Sensors, etc.) • Surgical Instruments Mfg. (Forceps, biopsy needles, breast bracketing systems, etc.) • Orthopedic Instruments Mfg. (Force Plates, etc.) • Measuring Instruments Mfg. (Clinical Thermometers, etc.) • Auxiliary Instruments Mfg. (Surgical marking pens, etc.) • Service Providers (Research, Testing & Compliance Studies,...)	• Each SME is focusing on different surgical and medical needs • There are many diverse types of SMEs • Large firms have also different product portfolios • Many firms are ISO 9001 and 13485 certified
Pharmaceutical Preparation	• Manufacturers of Pharmaceuticals for Special Diseases (Cancer, Pulmonary Diseases, Chronic Pain, Vaccines, etc.) • Private Label Manufacturers • Contract Manufacturers (Manu-facturing, Research, etc.) • Health Care Service Providers (Cancer Care, etc.) • Consultancies (medical device software consulting, etc.) • Biotech Devices Manu-facturers (cell printer, etc.) • Implants & Grafts Manu-facturers • Veterinary Pharma-ceutical Manu-facturers • Neutra-ceuticals Manu-facturers (dietary supplements, etc.)	• Each SME is focusing on different diseases • There are many diverse types of SMEs • Large firms are focusing on widespread diseases • Many SMEs are collaborating with universities and other companies
Analytical Laboratory Instruments	• Laboratory Utensils (Injectors, etc.) • Blood Testing Analyzers • Viscometers	• SMEs focus on products not offered by large firms • SMEs produce products that are seen as commodities in this sector (injectors) • SMEs focus more on small size customers (laboratories) (w/ low cost solutions, better usability, etc.) • SMEs produce final products, no SME is producing parts & components • Large firms have a wide variety of offered products
Search, Detection, and Navigation Instruments	• Navigational Instruments (GPS Tracking Systems, etc.) • Nautical Search Instruments (Underwater Camera Systems, etc.) • Industrial Optical Guidance Instruments (Laser Projectors, etc.) • Atmospheric Monitoring Instruments (Particles Measurement, Emission Monitoring, etc.) • Aerospace Parts & Components (Bonded parts, etc.)	• Very few SMEs • Many SMEs produce and market final products • SMEs are operating in diverse businesses being the only "competitor" in MA (aerospace, navigational, nautical, etc.) • Many SMEs (~50%) don't even have web sites
Industrial Process Variable Instruments	• Temperature Measurement Equipment Mfg. (Data Loggers, etc.) • Temperature Measurement Parts & Components Mfg. (temperature sensors, etc.) • Temperature Control Equipment (Thermal Blocks, etc.) • Light Measurement Equipment Mfg. (IR Cameras, spectrometers, etc.) • Light Measurement Parts & Components Mfg. (IR detectors, etc.) • Special Measuring Equipment Mfg.(Temperature influencing factor measurement, etc.) • Special Measurement Service Provider (metallurgical failure analysis, etc.)	• In temperature measurement some SMEs offer the same products as the large firms • Many SMEs (~30%) produce parts & components • SMEs provide very special services (fire investigation, failure analysis, etc.) • Most of the SMEs in MA (~40%) focus on light measurement systems • The main customers of light measurement systems are research institutions and the military • Large firms are focusing on measuring industrial processes (gas flow, pressure, etc.)
Aircraft Engine and Engine Parts	• Make-to-Order Parts & Components (comparable to Machine Shops) • Special Aircraft Vehicle Manufacturing	• SMEs are make-to-order manufacturer (similar to machine shops) • Only a few companies and very few SMEs operate in this sub sector

Table 7: The first filtering of industries according to patent data for 2008-2012

NAICS	Notes	NAICS Explanation	Total # of patents (2008-2012)
3341		Computer and Peripheral Equipment	4572
3345		Navigational, Measuring, Electromedical, and Control Instruments	3443
3342		Communications Equipment	2396
3344		Semiconductors and Other Electronic Components	2233
3254		Pharmaceutical and Medicines	1774
333		Machinery	1438
3391		Medical Equipment and Supplies	1353
335		Electrical Equipment, Appliances, and Components	1079
3251		Basic Chemicals	956
3253	3253 3255 3256 3259	Other Chemical Product and Preparation	851
339	339 (except 3391)	Other Miscellaneous	675
332		Fabricated Metal Products	576
3343	3343 3346	Other Computer and Electronic Products	443
326		Plastics and Rubber Products	349
327		Nonmetallic Mineral Products	177
313	313-316	Textiles, Apparel and Leather	172
3361	3361-3363	Motor Vehicles, Trailers and Parts	151
3252		Resin, Synthetic Rubber, and Artificial and Synthetic Fibers and Filaments	113
3365	3365 3366 3369	Other Transportation Equipment	67
3364		Aerospace Product and Parts	58
~~337~~		~~Furniture and Related Products~~	~~58~~
~~322~~	~~322 323~~	~~Paper, Printing and support activities~~	~~48~~
~~331~~		~~Primary Metal~~	~~32~~
~~321~~		~~Wood Products~~	~~21~~
~~311~~		~~Food~~	~~19~~
~~312~~		~~Beverage and Tobacco Products~~	~~7~~

Table 8: The 2nd filtering according to R&D spending per worker in 2009 and Share of High STEM Knowledge Occupations in 2012

NAICS	Notes	NAICS Explanation	R&D spending per worker US wide in $ (2009)	Share of High STEM Knowledge Occupations in % (2012)
325400		Pharmaceutical and Medicines	143110	48
334200		Communications Equipment	91428	57
325300	3253 3255 3256 3259	Other Chemical Product and Preparation	78887	36
333000		Machinery	62268	44
334100		Computer and Peripheral Equipment	60339	71
336100	3361-3363	Motor Vehicles, Trailers and Parts	55252	31.5
334400		Semiconductors and Other Electronic Components	49612	50
334300	3343 3346	Other Computer and Electronic Products	28074	32
339100		Medical Equipment and Supplies	24343	33
336400		Aerospace Product and Parts	20501	60
325100		Basic Chemicals	14679	50
334500		Navigational, Measuring, Electromedical, and Control Instruments	14265	58
336533	3365 3366 3369	Other Transportation Equipment	13476	30
325200		Resin, Synthetic Rubber, and Artificial and Synthetic Fibers and Filaments	11110	46
339000	339 (except 3391)	Other Miscellaneous	8547	23
~~335000~~		~~Electrical Equipment, Appliances, and Components~~		
~~332000~~		~~Fabricated Metal Products~~		
~~326000~~		~~Plastics and Rubber Products~~		
~~327000~~		~~Nonmetallic Mineral Products~~		
~~313000~~	~~313-316~~	~~Textiles, Apparel and Leather~~		
			approximate value	

Table 9: The third filtering based on employment data for 2013

NAICS	Notes	NAICS Explanation	Total # of employees
334500		Navigational, Measuring, Electromedical, and Control Instruments	24831
333000		Machinery	16988
334400		Semiconductors and Other Electronic Components	14997
334100		Computer and Peripheral Equipment	12373
336400		Aerospace Product and Parts	11467
339100		Medical Equipment and Supplies	10926
325400		Pharmaceutical and Medicines	9322
~~339000~~	~~339 (except 3391)~~	~~Other Miscellaneous~~	~~8636~~
~~325300~~	~~3253 3255 3256 3259~~	~~Other Chemical Product and Preparation~~	~~4063~~
~~334200~~		~~Communications Equipment~~	~~2668~~
~~325200~~		~~Resin, Synthetic Rubber, and Artificial and Synthetic Fibers and Filaments~~	~~2341~~
~~325100~~		~~Basic Chemicals~~	~~1187~~
~~336100~~	~~3361-3363~~	~~Motor Vehicles, Trailers and Parts~~	~~1106~~
~~336533~~	~~3365 3366 3369~~	~~Other Transportation Equipment~~	~~427~~
~~334300~~	~~3343 3346~~	~~Other Computer and Electronic Products~~	~~0~~

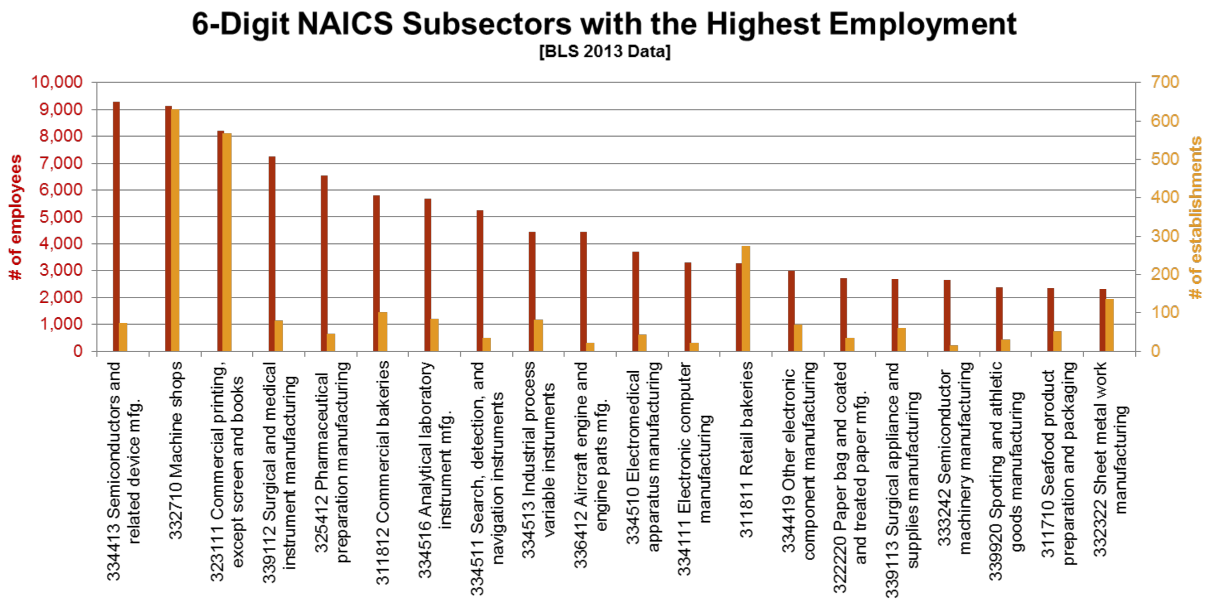

Figure 14: The Top 20 Subsectors in terms of employment on the 6-digit NAICS level

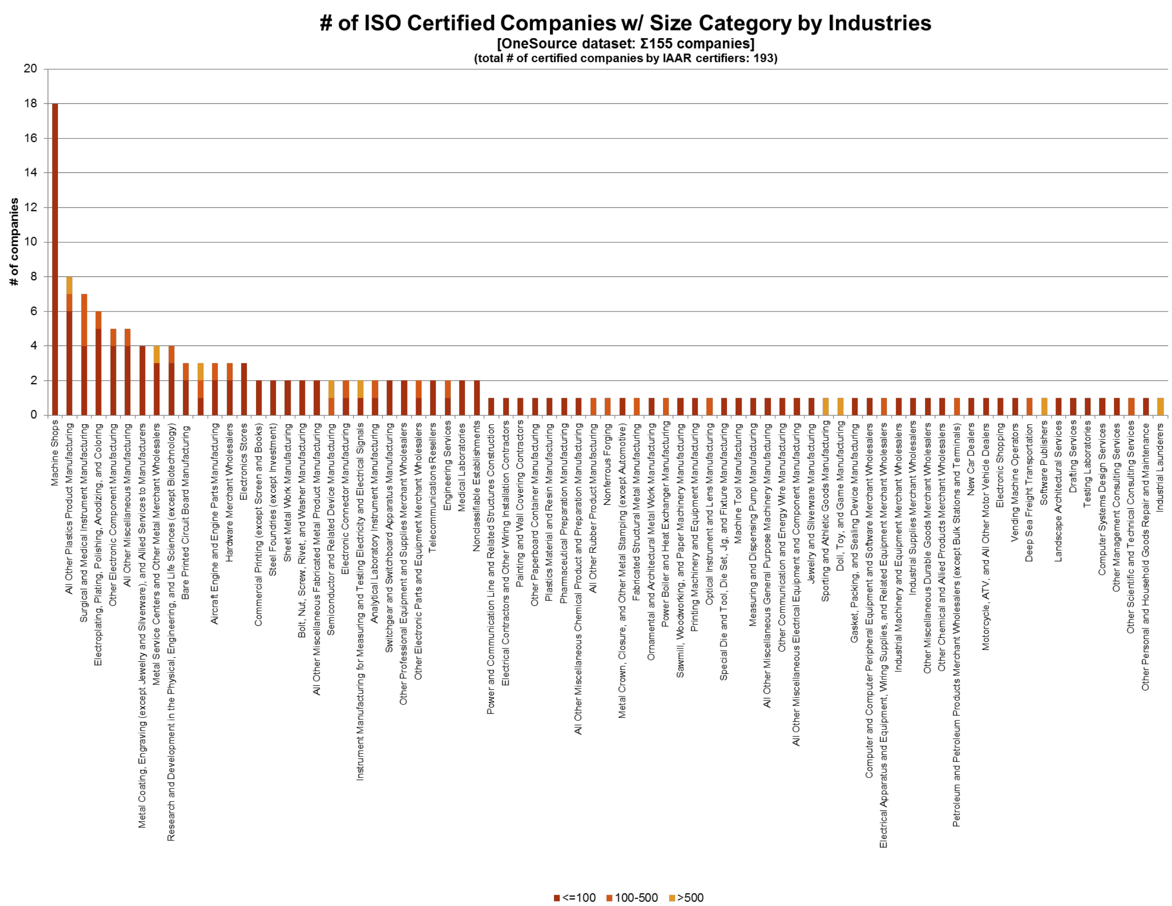

Figure 15: Number of ISO-certified companies by industry [57] & [22]

Table 10: Wage analysis of 4-digit manufacturing subsectors in MA

NAICS 4-Digit Industry	Total Annual Wages	Annual Average Weekly Wage	Annual Wages per Employee	Annual Average Employment Location Quotient	Total Annual Wages Location Quotient
NAICS 3341 Computer and peripheral equipment mfg.	1,858,911,534	2,889	150,242	322	262
NAICS 3254 Pharmaceutical and medicine manufacturing	1,131,010,069	2,333	121,327	137	118
NAICS 3345 Electronic instrument manufacturing	2,790,005,923	2,161	112,359	257	255
NAICS 3364 Aerospace product and parts manufacturing	1,239,433,405	2,079	108,085	94	89
NAICS 3332 Industrial machinery manufacturing	433,696,794	1,974	102,632	161	183
NAICS 3353 Electrical equipment manufacturing	248,204,836	1,973	102,585	68	84
NAICS 3344 Semiconductor and electronic component mfg.	1,505,125,765	1,930	100,363	164	144
NAICS 3322 Cutlery and handtool manufacturing	354,168,214	1,884	97,952	381	541
NAICS 3342 Communications equipment manufacturing	259,482,756	1,870	97,263	106	83
NAICS 3252 Resin rubber and artificial fibers mfg.	208,649,781	1,714	89,116	104	93
NAICS 3255 Paint coating and adhesive manufacturing	143,259,454	1,664	86,535	116	118
NAICS 3391 Medical equipment and supplies manufacturing	917,857,655	1,616	84,010	146	15
NAICS 3221 Pulp paper and paperboard mills	148,298,697	1,565	81,393	7	58
NAICS 3351 Electric lighting equipment manufacturing	147,943,440	1,553	80,763	161	183
Massachusetts Average, NAICS 31-33			79,854		
NAICS 3312 Steel product mfg. from purchased steel	46,342,327	1,499	77,930	42	44
NAICS 3251 Basic chemical manufacturing	92,506,046	1,498	77,922	34	23
NAICS 3336 Turbine and power transmission equipment mfg.	112,843,175	1,452	75,485	62	51
NAICS 3241 Petroleum and coal products manufacturing	59,797,285	1,441	74,942	29	16
NAICS 3329 Other fabricated metal product manufacturing	385,049,564	1,433	74,539	76	79
NAICS 3339 Other general purpose machinery manufacturing	301,440,206	1,427	74,219	65	6
NAICS 3253 Agricultural chemical manufacturing	8,738,573	1,396	72,569	13	1
NAICS 3321 Forging and stamping	140,581,232	1,346	70,011	83	89
NAICS 3334 Hvac and commercial refrigeration equipment	79,435,345	1,312	68,234	37	4
NAICS 3359 Other electrical equipment and component mfg.	281,363,147	1,309	68,063	134	118
NAICS 3333 Commercial and service industry machinery	192,252,559	1,309	68,048	132	108
NAICS 3324 Boiler tank and shipping container mfg.	74,793,191	1,268	65,960	48	43
NAICS 3112 Grain and oilseed milling	46,241,024	1,259	65,489	48	38
NAICS 3314 Other nonferrous metal production	103,919,141	1,254	65,214	103	86
NAICS 3256 Soap cleaning compound and toiletry mfg.	58,359,213	1,253	65,133	35	29
NAICS 3114 Fruit and vegetable preserving and specialty	127,434,021	1,250	65,020	46	55
NAICS 3259 Other chemical product and preparation mfg.	90,361,719	1,249	64,950	67	55
NAICS 3162 Footwear manufacturing	79,277,452	1,235	64,240	359	442
Massachusetts Average, all industries			62,311		
NAICS 3279 Other nonmetallic mineral products	89,082,291	1,197	62,266	83	82
NAICS 3133 Textile and fabric finishing mills	112,766,466	1,177	61,209	221	252
NAICS 3121 Beverage manufacturing	172,533,341	1,175	61,104	62	61
NAICS 3327 Machine shops and threaded product mfg.	653,701,104	1,175	61,103	119	117
U.S. Average, NAICS 31-33			61,102		
NAICS 3115 Dairy product manufacturing	133,479,959	1,169	60,783	67	6
NAICS 3261 Plastics product manufacturing	680,404,777	1,164	60,521	87	9
NAICS 3231 Printing and related support activities	695,414,350	1,157	60,176	104	111
NAICS 3273 Cement and concrete product manufacturing	111,571,181	1,151	59,848	45	43
NAICS 3335 Metalworking machinery manufacturing	183,089,732	1,149	59,773	7	6
NAICS 3323 Architectural and structural metals mfg.	295,688,323	1,147	59,651	58	57
NAICS 3399 Other miscellaneous manufacturing	513,168,252	1,143	59,420	128	124
NAICS 3222 Converted paper product manufacturing	397,665,937	1,139	59,232	101	86
NAICS 3362 Motor vehicle body and trailer manufacturing	17,426,538	1,138	59,157	9	9
NAICS 3366 Ship and boat building	24,754,961	1,115	57,985	13	1
NAICS 3117 Seafood product preparation and packaging	123,442,443	1,083	56,302	237	265
NAICS 3272 Glass and glass product manufacturing	61,592,192	1,075	55,912	55	47
NAICS 3313 Alumina and aluminum production	14,992,234	1,041	54,140	19	14
NAICS 3262 Rubber product manufacturing	57,150,993	1,039	54,005	33	27
NAICS 3352 Household appliance manufacturing	30,289,689	1,029	53,523	4	29
NAICS 3372 Office furniture and fixtures manufacturing	94,938,826	1,012	52,646	73	66
NAICS 3363 Motor vehicle parts manufacturing	42,479,841	1,007	52,380	6	5
NAICS 3315 Foundries	31,990,233	1,003	52,151	2	16
NAICS 3371 Household and institutional furniture mfg.	85,164,815	990	51,459	3	34
NAICS 3326 Spring and wire product manufacturing	25,925,636	984	51,144	49	42
NAICS 3119 Other food manufacturing	172,512,838	978	50,872	77	6
NAICS 3331 Ag. construction and mining machinery mfg.	9,903,257	975	50,699	3	2
NAICS 3328 Coating engraving and heat treating metals	207,256,615	962	50,022	124	11
NAICS 3132 Fabric mills	77,053,047	958	49,805	115	108
U.S. Average, all industries			49,701		
NAICS 3116 Animal slaughtering and processing	96,833,872	952	49,504	17	19
NAICS 3219 Other wood product manufacturing	93,631,584	919	47,796	4	43
NAICS 3169 Other leather product manufacturing	17,831,631	906	47,132	133	132
NAICS 3379 Other furniture related product manufacturing	24,808,336	892	46,363	63	57
NAICS 3212 Plywood and engineered wood product mfg.	8,617,376	864	44,921	12	1
NAICS 3325 Hardware manufacturing	11,849,099	857	44,587	46	29
NAICS 3311 Iron and steel mills and ferroalloy mfg.	4,082,180	823	42,783	4	2
NAICS 3161 Leather and hide tanning and finishing	2,606,400	789	41,046	65	44
NAICS 3149 Other textile product mills	62,957,086	783	40,714	101	95
NAICS 3113 Sugar and confectionery product manufacturing	44,489,697	685	35,606	75	46
NAICS 3118 Bakeries and tortilla manufacturing	385,226,125	664	34,522	16	123
NAICS 3141 Textile furnishings mills	18,785,925	662	34,401	43	3
NAICS 3131 Fiber yarn and thread mills	4,636,678	643	33,458	2	15
NAICS 3211 Sawmills and wood preservation	7,165,816	641	33,329	1	7
NAICS 3152 Cut and sew apparel manufacturing	59,638,037	580	30,179	68	46
NAICS 3111 Animal food manufacturing	931,113	523	27,186	3	1

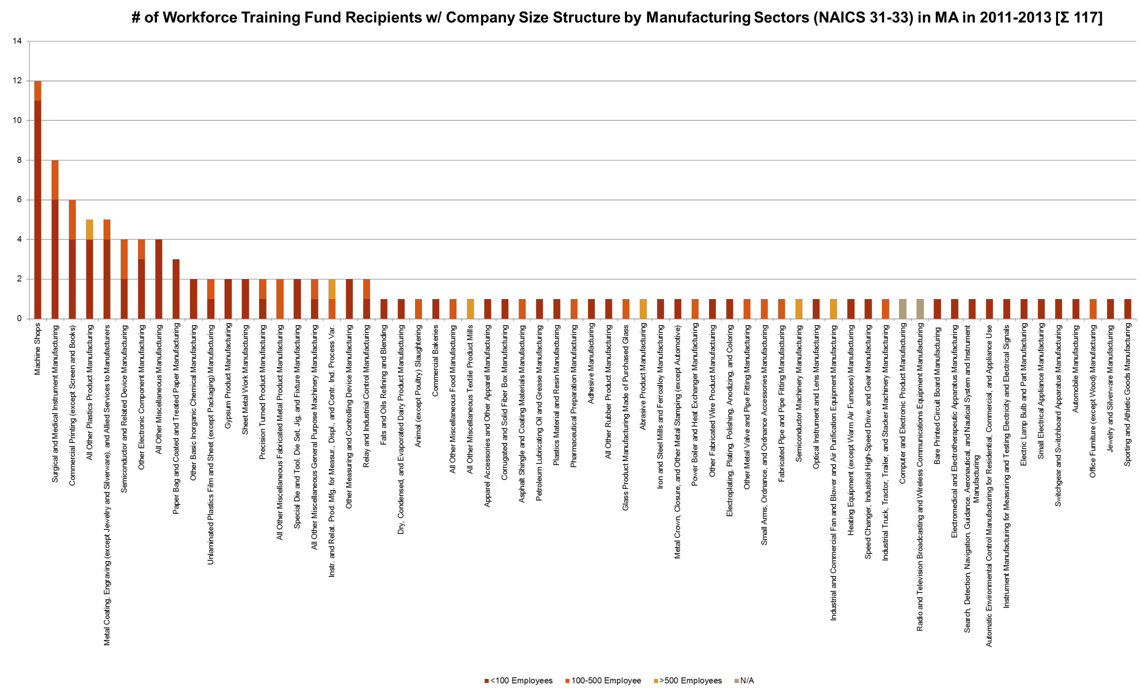

Figure 16: Subset of manufacturers receiving Workforce Training funds by industry between 2011 and 2013 [58] & [22]

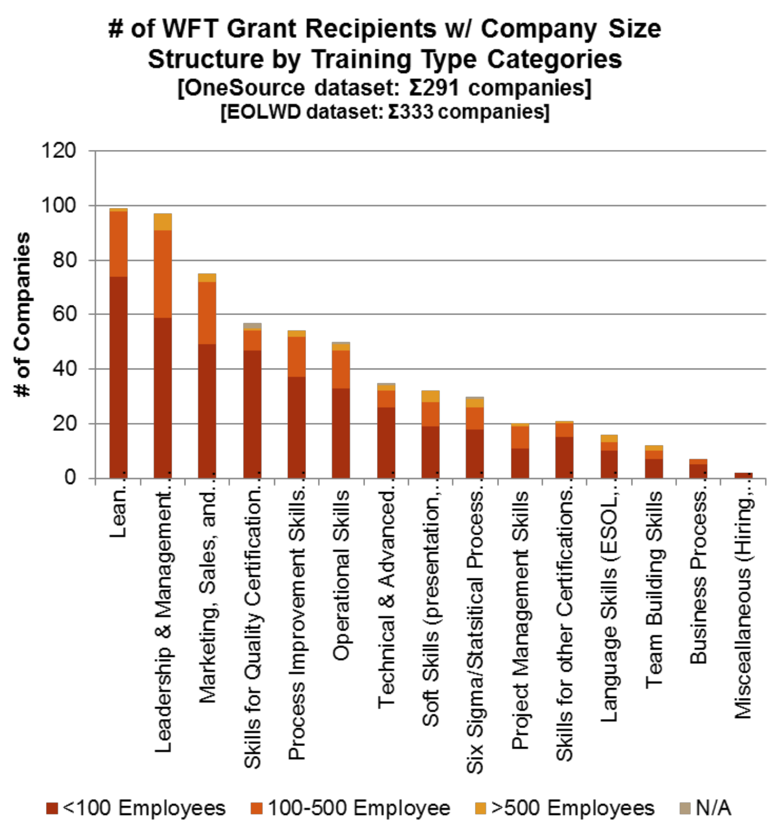

Figure 17: Training types of awarded Workforce Training grants across all industries between 2011 and 2013 [58] & [22](*note: more than one training type per grant is possible*)

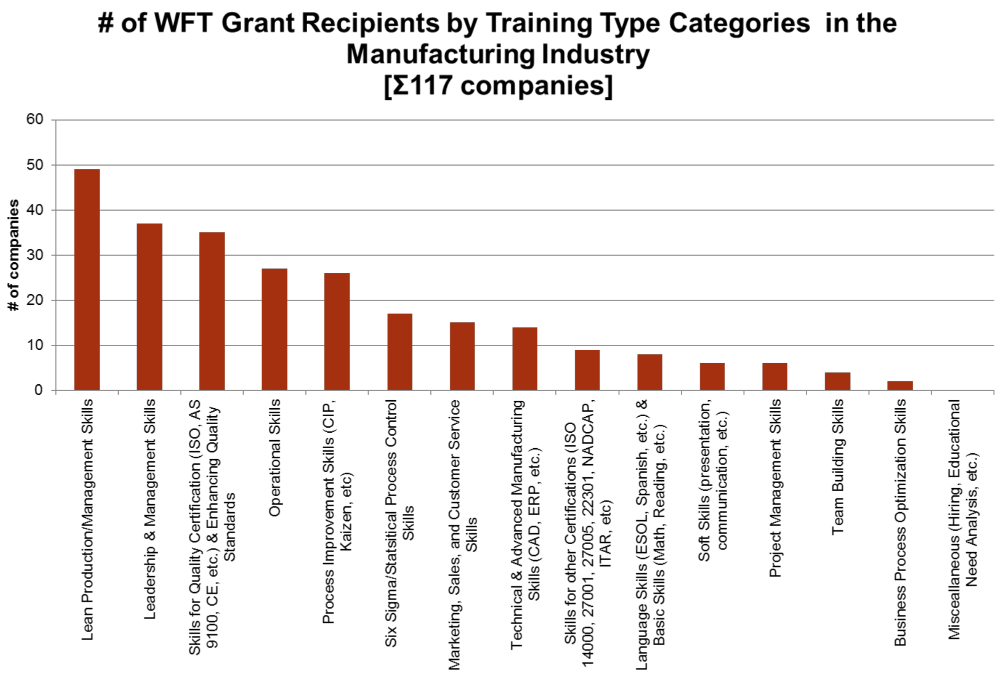

Figure 18: Training types of awarded Workforce Training grants in the manufacturing industry between 2011 and 2013 [58] & [22](*note: more than one training type per grant is possible*)

Table 11: Interviewed companies and institutions in the United States and in Germany

	U.S.A.	Germany
OEMs	Analog Devices	BMW AG, Munich
	Brooks Automation, Inc.	Miele, Gutersloh
	Covidien	Siemens Healthcare, Erlangen
	EMC Corp.	
	GE Aviation	
	Medtronic, Inc.	
	MKS Instruments, Inc.	
	Nypro	
	Pratt & Whitney	
	Raytheon Integrated Defense Systems	
SMEs	AccuRounds	
	Aerodyne Research	Corscience, Erlangen
	Boston Centerless	CT Imaging, Erlangen
	Boston Engineering	Hufschmied, Bobingen
	East Coast Welding	Innolite, Aachen
	EOS Photonics	KEX, Aachen
	Governors America	Munich Composites, Munich
	Hayden Corp.	
	M&H Engineering	
	New England Die Cutting, Inc.	
	OASIS, Inc.	
	Overlook Industries	
	Paperlogic	
	Science Research Laboratory, Inc.	
	Vention Medical	
	Williamson Corp.	
Intermediaries	Connecticut Center for Advanced Technology (CCAT)	German Ministry for Education and Research (BMBF) – Regional Innovation Initiatives, Berlin
	Fraunhofer Center for Manufacturing Innovation	German Ministry for Education and Research (BMBF) – New Innovation Support Instruments and Programs, Berlin
	Massachusetts Center for Advanced Design and Manufacturing (MCADM)	It's OWL Leading-Edge Cluster, Paderborn
	Massachusetts Institute of Technology (MIT)	Medical Valley Leading-Edge Cluster, Erlangen
	Massachusetts Manufacturing Extension Partnership (MassMEP)	MAI Carbon Leading-Edge Cluster, Munich
	MassDevelopment	RWTH Cluster of Excellence, Aachen
	Massachusetts Technology Collaborative	
	UMass Amherst	
	UMass Amherst Innovation Institute	
	UMass Lowell Mark and Elisia Saab Emerging Technologies and Innovation Center	
	Western Massachusetts Chapter of the National Tooling and Machining Association	
	Wisconsing Manufacturing Extension Partnership	

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