MIT work OF THE FUTURE

WORKING PAPER SERIES

Strengthening Manufacturing Innovation Ecosystems Before, During, and After COVID: Lessons from Massachusetts

Elisabeth Reynolds, PhD
lbr@mit.edu

Dan Traficonte
dtraf@mit.edu

Anna Waldman-Brown
annawb@mit.edu

MIT Work of the Future Working Paper 11-2021

January 22, 2021

MIT INDUSTRIAL PERFORMANCE CENTER

400 Main Street, E19-733, Cambridge, MA 02139

Strengthening Manufacturing Innovation Ecosystems Before, During, and After COVID: Lessons from Massachusetts[1]

Elisabeth Reynolds, PhD MIT DUSP and IPC; lbr@mit.edu
Dan Traficonte MIT DUSP and IPC; dtraf@mit.edu
Anna Waldman-Brown MIT DUSP and IPC; annawb@mit.edu

I. Introduction

Concerns about structural weaknesses in the US manufacturing sector have been voiced for decades, particularly since the dramatic decline in manufacturing establishments and jobs following the 2000 recession. A common thread in these analyses was the hollowing out of the shared institutional infrastructure—alternatively, the *manufacturing ecosystem*—that firms could turn to for support. Work by MIT researchers and others pointed to the loss of critical capabilities in the American manufacturing base and had long highlighted the problem that manufacturers, particularly small and medium-size, were "home alone" when it came to finding the institutional support they needed to increase productivity and innovate (Bonvillian and Singer 2018; Berger 2013; Glasmeier 2000; Cohen and Zysman 1987). As larger firms became more vertically disintegrated, outsourcing and offshoring many of their activities, the positive spillovers and public goods that they once provided both to their suppliers as well as the communities within which they operated, disappeared. Without increased attention and investments, experts warned that the U.S. was jeopardizing its national security, capacity to innovate, and economic growth opportunities more broadly, while other countries continued to make massive investments in manufacturing capabilities across a range of technologies and industries (Shih and Pisano 2012).

In part, these warnings were heeded. Since the start of the recovery from the Great Recession of 2008, there has been a flurry of new interventions by both the public and private sectors aimed at recovering lost ground and reviving the dynamism of American manufacturing. This recommitment to manufacturing was led in part by the federal government under the Obama Administration, with the largest federal investment in manufacturing in over 20 years (approximately $600 million (Manufacturing USA 2020)). Many state governments invested alongside the federal government, and also launched new initiatives which have catalyzed additional investments by cities, universities and non-profits, prioritizing manufacturing as an important part of their economic development strategy. State-level manufacturing ecosystems, though still lacking the institutional strength of industrial ecosystems in Germany or Japan, have to some degree rebounded and have the potential to support an American industrial comeback (Armstrong 2019).

Despite major investments and rebuilding in recent years, the COVID-19 pandemic exposed continued structural weaknesses and vulnerabilities in American manufacturing. As the crisis exploded in the United States in March of 2020, and continued into the fall, massive shortages across the country of personal

[1] We would like to thank the Joyce Foundation for their generous support of this research. We would also like to thank our colleagues Ben Linville-Engler, Haden Quinlan, and Carolyn Kirk for their thoughtful and thorough input to the paper as well as Farhad Vazehgoo for his excellent insights. Finally, we'd like to thank Ira Moskowitz for generously making M-ERT meetings and materials accessible to the team from the outset.

protective equipment (PPE), and more recently product testing equipment for new entrants to the PPE market, have revealed the fragility of the country's domestic manufacturing capabilities when faced with a sudden shock to global supply chains and a lack of federal intervention. American industry's vulnerabilities have been on full display as healthcare providers in hot-spots nationwide struggle to find able suppliers who can meet quality, quantity and timeliness demands. The country's sclerotic domestic supply chains have been slow to meet the new production challenge, and – in the absence of robust leadership from the federal government – state and local governments have been forging their own paths forward. While some crises have been averted, others may still lie ahead. Regardless, there is general agreement that the need for PPE for health care workers and other front-line workers will not abate for many months to come.

State-level responses to the shortages of PPE and testing equipment have varied dramatically. While some states continue to scramble for medical supplies as infection rates remain high, other states, including Massachusetts, have managed to largely avert a supply crisis by mobilizing local and regional manufacturing ecosystems. State-level ecosystems have played a critical role in states' COVID-19 response plans—or lack thereof—and have enabled some states to draw on the full range of productive capacities embedded in their local economies.

What has helped some states respond to the crisis better than others? We argue in this paper that recent public and private-sector investments in regional manufacturing ecosystems, specifically in Massachusetts, have played a critical role in mobilizing manufacturers to produce PPE and creating resiliency in the economy more broadly. Investing in rebuilding manufacturing both in terms of firm capabilities as well as organizational capabilities in the state over the last 5-8 years has created a solid foundation that could be quickly mobilized in the face of a state-wide and national crisis. In particular, we show that the state government's prior ecosystem investments and pre-existing relationships with key stakeholders allowed for the quick deployment of the Massachusetts "Manufacturing Emergency Response Team" (M-ERT), a group that was able to identify capable manufacturers and help them pivot and ramp up production of PPE. The successful initial rollout of M-ERT is a positive byproduct of the investments made in previous years to strengthen manufacturing and position the state to compete globally.

As the country faces the dual threat of economic downturn and public health crisis, manufacturing ecosystems are proving critical to both the resiliency of local economies and the mobilization of healthcare resources. The percentage of US manufacturers surveyed by the National Association of Manufacturers who were positive about their own company's outlook rose from a low of 34% in May 2020 (the lowest since early 2009) to 66% in September 2020 (NAM 2020). Anecdotally, all of the manufacturers we interviewed for this research were classified as essential firms and none of them shut down entirely during the pandemic.

With respect to mobilizing the ecosystem for healthcare resources, we demonstrate that recent investments in the state's manufacturing ecosystem bolstered the state government's response to the COVID-19 crisis and the rapid ramp-up of PPE production by manufacturers in the state and beyond. The basic infrastructure already in place as a result of recent ecosystem investments helped Massachusetts avoid worst-case scenarios in medical supplies and move more quickly to support the state's health care providers.

Though M-ERT arose from the existing ecosystem in Massachusetts in collaboration with subject matter experts as a response to an acute crisis, it underscores not only what should be taken forward to better prepare for the next "black swan" event, but more broadly, what investments in the manufacturing ecosystem can create more resiliency, increase manufacturing capabilities and take advantage of opportunities for growth going forward. This paper outlines three key areas of new investment within the Massachusetts manufacturing ecosystem that largely played a role in the state's pandemic response: innovator institutions, broker institutions, and educators.

The following provides a closer look at some of the major investments in the state's manufacturing ecosystem as well as details about the creation and implementation of M-ERT. After a brief review of our research methods, section III provides an overview of the roots of manufacturing innovation ecosystems and the Massachusetts ecosystem specifically. Section IV highlights some of the most important new innovators, brokers and educators engaged with manufacturing in the state. Section V turns to the state's manufacturing response to the COVID-19 crisis and the creation of M-ERT, reviewing its organizational structure, activities, and challenges. Chapter VI concludes with a look post-COVID crisis at Massachusetts' manufacturing ecosystem and offers a set of priorities going forward that can better prepare the state for the next crisis while, most importantly, building a stronger, more resilient and more capable manufacturing ecosystem for years to come.

II. Research Methods

From 2018 to early 2020, our research team conducted in-person, semi-structured interviews with approximately 20 manufacturing firms and manufacturing ecosystem institutions across Massachusetts. These firms consisted mainly of small and medium enterprises (SMEs), with a few multinational corporations. We asked about firms' adoption of new technologies and implications for workers and skills, connections to specific institutions, and firms' general relationship to their local manufacturing ecosystem. We primarily interviewed the directors, owners or heads of operations of these organizations and involved factory tours where possible. Interviews were semi-structured and ranged from one to two hours.

The authors also participated in thrice-weekly, one-hour video calls and presentations organized by the state of Massachusetts Manufacturing Emergency Response Team (M-ERT) from early April through June 2020, which led our team to investigate the state-level COVID-19 manufacturing responses. We followed up for more information via direct emails and phone interviews with key stakeholders, and had access to slide decks and notes created by participants for internal reporting.

III. Manufacturing Innovation Ecosystems

Drawing from both economics and biology, the term "manufacturing ecosystem" has become a popular way to describe the economic, social and geographic dimensions of a region's manufacturing base. The roots of the concept can be found in the late 19th century economist Alfred Marshall's "industrial district" (1890), which emphasized the importance of agglomeration economies in explaining the presence of related firms in a concentrated geographic region, creating positive spillover effects for firms, institutions and workers through increasing specialization and the knowledge that is found "in the air." A century later, Markusen (1996, p.294) provided a modern typology to identify the role of both state and private sector in anchoring industrial districts or "sticky places," by "providing the glue that makes it difficult for smaller firms to leave, encouraging them to stay and expand, and attracting newcomers into the region." In their literature review, Scaringella and Radziwon (2018) trace how this concept morphed into the idea of a "business ecosystem," deriving language from biology. Biological ecosystems are comprised of all living organisms within a physical environment functioning together as a unit, and seeking an equilibrium state with stable conditions to maintain desirable population levels (Jackson 2011). Creating the conditions in which firms and institutions in a region build inter-dependencies that reinforce their survival and growth does not seem too far a metaphorical stretch.

More recently, creating and sustaining "innovation ecosystems" have become a central goal of regional economic development strategies. Innovation is broadly defined as a new or improved product, process, or combination thereof that has been made available to potential users (OECD Oslo Manual 2018). The nature of the innovation process involves not only what occurs within the firm, but also the external environment that can spur and encourage innovation through knowledge transfer, specialized labor and suppliers and access to capital; thus, investing in the institutions, policies and programs that encourage a robust "innovation ecosystem" has been a priority for government in partnership with private-sector and non-profit actors (Murray & Budden 2017).

With respect to manufacturing, a deeper appreciation of its importance to the innovation process as well as strategic priorities such as national security led to a renewed focus on manufacturing innovation ecosystems coming out of the Great Recession. This aligned with the emergence of new advanced manufacturing technology, "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" (PCAST 2011). The rise of these technologies, which has led to the creation of more "hybrid" products that combine hardware and software (such as wearables, medical devices, and autonomous vehicles), has injected more opportunity and interest (as measured at least by R&D dollars and risk capital) in American advanced manufacturing throughout the early 2000s than has been seen in decades.

Efforts to coordinate and enhance manufacturing innovation ecosystems are largely driven at the state and regional level. This is, in part, due to the geographic nature of ecosystems, grounded as they are in place and networks that are regional in nature (Markusen 1996). But this is also a function of the relatively limited role the federal government has played in investing in these ecosystems over time. The renewed focus at a federal level on manufacturing in the US was best exemplified by the creation of the Manufacturing USA network launched in 2012. The network consists of 14 centers, run by public-private partnerships aimed at catalyzing R&D and workforce development in a number of critical areas in advanced manufacturing, that support multiple industries such as robotics, photonics, materials science, and bioengineering. This effort, along with the Manufacturing Extension Partnership (MEP), represents America's largest direct federal programmatic investment in the nation's manufacturing capabilities. Obviously, investments in R&D, particularly by the Department of Defense, represent significant investments in manufacturing as part of the country's national security complex, albeit in particular technologies or products. These have had significant spillover effects in regions where DOD contractors and suppliers are located. A new federal "manufacturing community" initiative announced in 2020 also centers on supporting the defense industrial base (AMCC 2020). On the whole, however, the nation's research labs and agencies historically often prioritized other key industries or technologies, such as in the life sciences, over non-defense related manufacturing products and processes. So too have large manufacturers been largely prioritized over small manufacturers in the case of the work of the Manufacturing USA network (Traficonte 2020). The lack of a national manufacturing strategy or broader agenda in manufacturing has arguably led states to play a more prominent role in developing regional manufacturing ecosystems as a key part of their economic development agenda. The need for a more robust national manufacturing strategy was made apparent by the COVID-19 crisis. We take up this topic later in the paper.

The Massachusetts Manufacturing Ecosystem

The Massachusetts manufacturing ecosystem is a prime example of such state-level efforts. The manufacturing base in Massachusetts is somewhat small as a share of the state workforce, but economically significant in the broader picture of the state's economy. Manufacturing accounts for only 6.7% of employment in Massachusetts in 2018—compared to 12.6% in industrial heartland states like Ohio—but the average annual compensation for a Massachusetts manufacturing employee is near the highest in the nation, at slightly over $100,000 in 2020 compared to around $77,000 in Ohio (NAM, 2020). Massachusetts's small and medium sized enterprises (SMEs) are an integral part of the state's manufacturing ecosystem, with 97% of manufacturing firms employing fewer than 500 employees and accounting for around 30% of the state's total manufacturing employment. Hit particularly hard by the 2000s manufacturing decline and the Great Recession, Massachusetts lost around a third of its manufacturing establishments; the state dropped from roughly 10,000 firms in 2001 to 7,000 in 2013, which was twice the national rate of decline. The state's industrial base stabilized in the wake of the Great Recession, though manufacturing employment declined until 2018 when there was a modest increase for the next two years.

Manufacturing capabilities are critical to several of the state's most important industries or clusters, led by numerous multinational companies in such areas as aerospace and defense (Raytheon, GE, Lincoln Laboratory), biopharmaceuticals (Novartis, Biogen, Genzyme), medical devices (Boston Scientific, Medtronic, Thermo Fisher), and consumer products (EMC/Dell, Analog Devices, Bose, Gillette, New Balance). These companies rely on a highly educated and skilled workforce, strong research collaborations with world class universities, regional suppliers who can provide quick turnaround of quality parts, as well as exposure to a dynamic startup culture. The following attributes are listed as key characteristics of the state's manufacturing production system:

- Small-batch niche production, rather than large-volume mass production,
- Extreme 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.

There is a tight relationship between manufacturing and innovation in the state. Many firms engage in new product launch in Massachusetts because of its strength in prototyping and early stage scale up of new technologies, which in turn, relies upon sophisticated suppliers who can provide just-in-time quality parts (Reynolds and Uygun, 2017; Renski 2014). For all of these reasons, Massachusetts offers an important case study of how U.S. manufacturers in high wage locations compete in today's global economy and complex supply chains.

IV. New organizations and institutional models in Massachusetts

Massachusetts, like other states and the federal government, has prioritized manufacturing as part of the state's economic development strategy after the Great Recession (Reynolds and Uygun, 2017). Reports that emphasize the importance of manufacturing to the innovation process resonate in the Commonwealth given its strong innovation capacity; Massachusetts is consistently rated among the most innovative states in the country (ITIF, 2020; Hagan and Lu 2019; Klowden, Lee, and Ratnatunga 2018). In an effort to revitalize the state's manufacturing base and attract new talent to the industry, new investments have been made and a diversity of new institutional models have been created, often led by boundary-spanning actors that have already been active across the manufacturing sector. These programs and initiatives emerged through new consortia, often state-led, in partnership with the private sector as well as federal and sometimes municipal governments, many of which played a role in the state's pandemic response. These have been added to an existing number of organizations and institutions that have been in place for years (such as the Massachusetts Manufacturing Extension Partnership), and represent a renewed focus on the sector in the state.

Below we offer a typology to categorize these investments by their three primary functions: innovators, brokers, and educators. This typology draws in part from related research into the role of Research and Technology Organizations (RTOs), which often play a critical role in forging partnerships to support greater regional/state innovation (EARTO 2015). Table 1 lays out the significant new programs or institutions, along with their initial funding and focus. It is interesting to note that all of the reorganizations or new programs were initiated in just the past five years. We describe each of them in detail below.

Table 1: Selection of recently founded institutions by category (AFFOA 2020; Commonwealth of Massachusetts 2020; Diop 2017; personal interviews)

Institution	Year of new investment	Initial funding and source	Targets
INNOVATORS			
AFFOA	2016	Federal, State, and Private ($317M combined)	Large firms, startups, academia, SMEs (lesser focus)
M2I2	2016	State ($100M)	Large firms, SMEs, academia
MassRobotics	2017	State/Local ($2.75M), Federal ($466K in subcontracts)	Large firms, SMEs, startups
BROKERS			
Advanced Manufacturing Collaborative	Founded: 2011 Reinstated: 2019	N/A	Large firms, SMEs, workers
FORGE (a Greentown Labs initiative)	2015	Federal ($50K), State ($200K)	Startups, SMEs
EDUCATORS			
AIM Academy/LEAP	2017	Federal ($110M), State ($28M)	Workers, academia, community colleges
MassHire	Convened 2018 (re-org of existing workforce boards)	Annual budget of Federal and State (~$6.9M)	Workers, firms

A. INNOVATORS

In the context of manufacturing institutions, we classify "innovators" as the R&D facilities and institutions that focus primarily on identifying, scaling, and funding the development of new manufacturing products and processes (Reynolds and Uygun 2017). While many of the "brokers" and “educators” discussed below share the goal of improving innovation capabilities across their networks, these “innovators” are distinguished by their technology-driven approach and emphasis on investing in pre-competitive research and/or expensive capital equipment for emerging technologies.

Advanced Functional Fabrics of America (AFFOA)

In 2012, the Department of Defense launched what would become the Manufacturing USA program with $600 million in federal investment and $1.2 billion in matching funds from industry, academia and state governments to “form centers of excellence promoting U.S. competitiveness.” These fourteen institutes collectively represent nearly 1,000 American organizations spanning the public and private sectors (Manufacturing USA 2020). These Institutes were designed to do many things at once, reflecting the Obama Administration’s view that promoting technological development in manufacturing would require a multipronged approach (Holdren et al. 2012). Each institute acts primarily as an R&D consortium for a given manufacturing subfield, but also offers workforce development programs and, where necessary, provides physical space for industry and university members to carry out research projects.

Founded in 2016 with a grant from the Department of Defense, the Massachusetts-based Advanced Functional Fabrics of America (AFFOA) is one of the newest Manufacturing USA Institutes. The Institute’s primary mission is “the transformation of traditional fibers, yarns, and textiles into highly sophisticated integrated and networked devices and systems” (AFFOA, 2020). Advanced fabrics offer a wide range of potential applications, including “wearables” or sensor-embedded textiles. Unlike most other Manufacturing USA institutes, which often cater primarily to large firms, AFFOA’s membership firms skew towards small, high-tech startups as well as large defense contractors, multinationals, and several universities.

Given the early-stage nature of smart fabric technology, AFFOA’s key challenge lies in convincing its partner firms to collaborate on risky R&D. This has led the institute to focus more effort toward developing its own new technologies in-house, in order to first “prove up” the technology and then later disseminate it amongst its members. To this end, AFFOA has built out a large textile prototyping facility near MIT for its own researchers to develop and collaborate on projects. This has led to a more sustained engagement with the local ecosystem than can often be found at other institutes within the Manufacturing USA program, which are often only loosely embedded within their home state’s ecosystems. AFFOA’s unique approach to technology development has given the institute deep-seated ties with other institutional actors, including the state government, nearby universities, and local manufacturing firms. As we detail below, AFFOA’s embeddedness was a key part of its successful contribution to the state’s COVID-19 response.

Massachusetts Manufacturing Innovation Initiative (M2I2)

In an effort to leverage the federal government’s investments in Manufacturing USA, the state of Massachusetts created the Massachusetts Manufacturing Innovation Initiative (M2I2), the largest state-run manufacturing grant program in the nation. Begun in 2016, the M2I2 program provides capital cost shares for projects that include a university partner, meet the state and regional criteria for supporting economic development, and fit under one of four different Manufacturing USA institutes (AFFOA, AIM

Photonics, NextFlex, or Advanced Robotics Manufacturing). The program was launched with $100m available for investment over a fixed period. As of 2019, the program had invested over $50 million in grants to advanced manufacturing projects across the state, with the four Manufacturing USA institutes contributing a total of $18.6 million in cost-sharing (MassTech 2019).

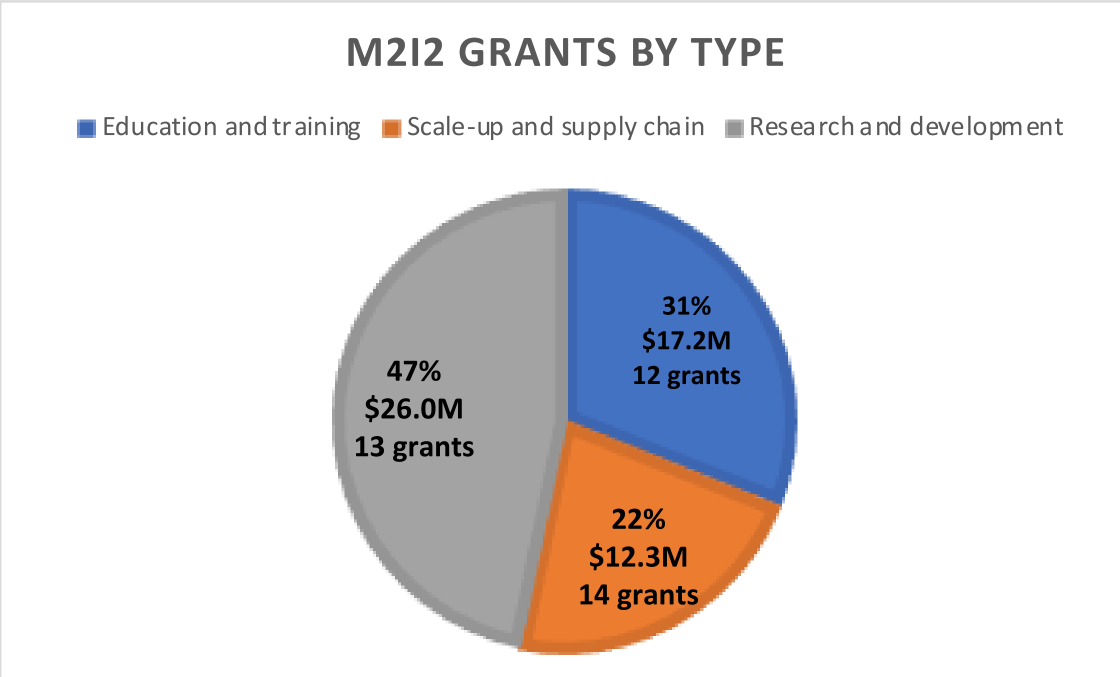

Figure 1: M2I2 grants sorted by category of grant

M2I2's projects are often cost-shared with the federal government, sometimes above the state's contributions. Selection criteria include new jobs created (or existing jobs saved), cluster-building or enhancing investments in key technologies or capabilities, and supporting Massachusetts businesses – especially outside the Greater Boston area – that can create positive economic spillovers for the state. The program goes beyond traditional state economic development programs in that it supports cutting-edge technologies in growing and risky industries, including providing capital grants directly to companies. M2I2 also devotes much of its effort towards technologically advanced SMEs, many of which would not be on the radar of the Manufacturing USA institutes. M2I2 leadership have been highly engaged in the state's manufacturing ecosystem, looking for and promoting new partnerships and potential projects for M2I2 to fund. The lead coordinator believes that state-level programs are much better at advertising their programs to firms than federal initiatives such as AFFOA. As detailed in Figure 1, M2I2 has made 39 investments to universities and firms in the past four years, of an average size of $1.44 million (M2I2 2020).

As an example of one such investment, a nanotech SME received a $2.3 million M2I2 grant to work with the NextFlex Manufacturing USA institute (based in California) to create an ecosystem around producing, printing, and packaging nano-lithography. M2I2 allowed them to spend half of their grant on purchasing equipment for one of their Massachusetts suppliers who couldn't otherwise meet their quality standards. Investing in new technology and equipment is often a hurdle for small suppliers of high-tech companies. The nanotech firm's owner insisted that any strong manufacturing ecosystem needs "a common language and common capability, so it looks like a full system for our customer base." This type of investment in cluster building through strengthening a supply chain is indicative of M2I2's investment strategy. While traditional economic development initiatives just measure success in terms of direct job creation, M2I2's investments are geared toward developing high-tech and long-term manufacturing ecosystems. The founder/coordinator of M2I2 often relies upon the well-established but rarely innovation-focused Manufacturing Extension Partnership (see Appendix) to communicate its resources out to firms statewide, and he believes that this MassMEP is "probably the best vehicle the state has for popularizing these [grant-giving] activities."

MassRobotics

MassRobotics, which opened its doors in a former warehouse in the Boston Seaport in 2017, is an independent nonprofit that supports the state's robotics industry. It was co-founded by local industry partners such as Joyce, Amazon, and Vecna to support smaller SMEs and startups, as well as the overall robotics ecosystem across the state. The organization has three components: supporting the over 250 Massachusetts firms working on robots, from Amazon to one-person startups; running events such as networking gatherings, educational programs, and conferences to promote robotics; and hosting a shared, reduced-cost workspace to advise and incubate robotics startups while providing shop space, software, and equipment. In 2020, MassRobotics hosted around 45 companies working on a wide variety of robotics startups, plus several robotics research collaborations with government agencies and multinational firms.

Initial funding and support for MassRobotics came in partnership between the City of Boston and the state's MassWorks fund) which helped them gain access to affordable rent and funding for renovation in a city-owned warehouse. The City then helped MassRobotics to successfully apply for three Mass Tech Collaborative grants totaling $165,000 for purchasing robotic arms, promoting STEM education, and promoting robotics statewide. MassRobotics also received a $100,000 grant from MassCEC to encourage the use of robotics in the clean energy sector. They have also received $466,000 in federal subcontracts by partnering with teams that received funding from the Department of Defense, the National Science Foundation, and the Manufacturing USA Advanced Robotics Manufacturing Institute (ARM) out of Pittsburgh. MassRobotics has since worked with a number of Massachusetts institutions and private firms on supplying robots and networking, and brought in several Massachusetts SMEs to contribute to larger university-led projects.

B. BROKERS

Several new institutional models have proven especially impactful in bringing together stakeholders across public and private sectors, connecting firms across supply chains, and strengthening regional capabilities through new collaborations and resources. We classify these as "broker" institutions and detail critical examples here. Of course, as with the innovators, there are other existing brokers in the state, such as the 30-year-old Massachusetts Extension Partnership (MassMEP), which brings advice and expertise to small and medium-size manufacturers. We are focused here on those new institutions and arrangements that have been introduced in the past five plus years (MassMEP is detailed in the Appendix).

The Advanced Manufacturing Collaborative (AMC)

In 2011, as President Obama's Advanced Manufacturing Partnership and the Manufacturing USA initiatives got under way, the Advanced Manufacturing Collaborative (AMC) was created to enhance statewide manufacturing competitiveness through promotion, workforce and education, technical assistance, and access to capital. The AMC, chaired by the Secretary of Housing and Community Economic Development and managed by the state's quasi-public economic development entity, the Massachusetts Technology Collaborative, developed a state-wide manufacturing strategy that became the foundation for the state's manufacturing work over the next decade. In 2019, Governor Baker's administration reconfigured the AMC to expand inclusion of larger firms and launched three working groups: Innovation and Ecosystems, Talent and Branding, and the Business Environment. In its meetings pre-COVID-19, the AMC was focused on talent development as a key priority for the state given the shortage of workers (both engineers and technicians) and had recently launched a program at the state's vocational schools to help fill the pipeline of demand by manufacturers. While many of Massachusetts's manufacturing initiatives follow a top-down structure, the AMC actively engages a variety of institutional actors across all levels of involvement. As discussed later, this state-wide strategy played a key role in both launching the M-ERT response as well as facilitating the networking that helped connect stakeholders to develop a robust and grassroots statewide response to COVID-19.

FORGE (a Greentown Labs initiative)

The cleantech incubator Greentown Labs in Cambridge founded the nonprofit FORGE (formerly Greentown Learn) in 2015 to help clean energy-oriented startups find Massachusetts-based manufacturing suppliers for prototyping and pilot production of their products. Annually, FORGE receives about $125,000 in foundation funding and $400,000 in revenue. FORGE has facilitated the creation of over 140 contracts between their network of startups and suppliers, with a known economic value of over $30 million in known contracts and purchase orders for local production. The program has reached over 200 startups, both within Greentown's cleantech network as well as consumer products, medical devices, aerospace and transportation, robotics, and more (FORGE 2020). FORGE is headquartered in Somerville at Greentown Labs, and opened an office in Springfield in early 2020 to support Western Massachusetts manufacturers as the first of several planned additional locations across the state.

C. EDUCATORS

A third category identified in the course of our research is a set of institutions engaged in cross-sectoral training and skills-development programs, many of which have created pathways for workers to get into manufacturing for the first time. Workforce education and training is seen as a critical piece of building the state's ecosystem given the shortage of workers the industry has faced (at least pre-COVID). Though these institutions have played a lesser role in the state government's successful mobilization in response to COVID-19, they nonetheless provide further illustration of the state's commitments to reinvesting in the ecosystem in recent years.

AIM Photonics Academy and other Labs for Education and Application Prototypes (LEAPs)

Across the Manufacturing USA institutes, several stakeholders identified a significant gap between the cutting-edge R&D within these institutes and the existing workforce training programs across community colleges and other programs which cater to developing technical skills among lower and moderate-educated workers. The American Institute for Manufacturing (AIM) Integrated Photonics Academy was founded in Cambridge, MA as the educational arm of the Manufacturing USA Institute AIM (based in Albany, New York) in order to train a new generation of photonics technicians. Integrated photonics is a relatively new set of technologies that uses optical circuits to process and transmit light signals, similar to how computer chips route electrical signals through components. Integrated photonics have applications in fields as diverse as lasers, machine vision, circuitry, and cellphone networks.

The program began with a federal grant of $110 million from 2017-2022, as well as a state grant of $28 million to launch AIM Photonics initiatives, including several Lab for Education and Application Prototypes (LEAP) facilities spread across the state to provide workforce training around photonics. AIM Academy is based at MIT, where integrated photonics technology originated, and directed by an MIT professor of materials science. The Academy provides practical training through for-credit courses, bootcamps, and internships for university and community college students. It involves a range of other universities and community college partnerships, and has served as a model for the expansion of other LEAP labs with educational institutions throughout the state (most recently, Bridgewater State University and Stonehill College in the end of 2019) in partnership with other Manufacturing USA institutes. Other partners include large firms involved in photonics such as Lockheed Martin, who have sent their engineers and technicians to AIM Photonics Academy or employed AIM's online courses to train workers in emerging photonics technologies and manufacturing processes (Rosen 2018).

MassHire

In 2018, Massachusetts became the only state in the nation with a coordinated, statewide umbrella that unites the state's 16 regional workforce boards into a single coalition called MassHire. MassHire is run through the state's executive Office of Labor and Workforce Development, and combines 25-30 local workforce centers under a single, statewide brand with a shared set of objectives and grants for target areas. Following this reorganization, firms became more aware that individual boards were all part of a statewide organization and they began to reach out to MassHire for useful referrals statewide (see Figure 2). In addition to helping firms identify and train workers, MassHire also helps small firms stay aware of funding opportunities and labor regulations at the federal and state levels. As one workforce board director said, "we are the glue."

One of MassHire's statewide workforce focuses is manufacturing, although each workforce board must develop its own targeted strategic plan depending on the manufacturing sectors in that region; North Central is focused primarily on paper goods, pharmaceuticals, and prototyping whereas New Bedford targets textiles and apparel. MassHire's efforts are focused on coordinating with industry, providing education and training, as well as rebranding "what manufacturing is really like in today's world" to change workers' impressions of the manufacturing sector. The program's goal statewide is to get workers into lower-level shopfloor positions that have the potential for lifelong career ladders. The state has also developed a variety of new grants to connect SMEs with community colleges and other educational institutions, which led to the reinvestment in vocational-technical schools across the Commonwealth starting around 2016.

In 2019, the state changed its workforce training policy to switch to a competitive bidding process, in which private firms that demonstrate a long-term commitment to training can bid for multi-year, workforce development grants.

Figure 2: Map of 2018 MassHire workforce development areas statewide (Commonwealth of Massachusetts 2019)

Takeaways

These examples highlight the multiple ways that investments in the Massachusetts manufacturing ecosystem in the past five plus years have created new, innovative models for spurring more R&D, facilitating partnerships and networks, and training a much needed (at least pre-COVID) pipeline of workers in advanced manufacturing skills. As we outline in the next section, many of these new investments, combined with existing elements of the ecosystem, helped position the state well to respond to the COVID-19 crisis.

V. Mobilizing the Ecosystem in Response to COVID-19

On January 31, 2020, Secretary of Health and Human Services Alex Azar II issued a Public Health Emergency Declaration for COVID-19, which enabled the Food and Drug Administration (FDA) to begin drafting response regulations. The FDA then started reaching out to manufacturers to understand what shortages existed in case the virus spread overseas. When the COVID-19 crisis actually hit the US in late February and early March, the attention of policymakers first turned to the federal government to marshal a supply-side response to the emerging public health scare. On March 17, 2020, with COVID-19 cases surging in New York City, the White House declared the PREP Act which provided liability immunity for manufacturers producing medical countermeasures (e.g. PPE) as long as their products were approved, cleared, or authorized by the FDA. (Under normal circumstances, manufacturers of such devices would be vulnerable to lawsuits since the FDA does not normally provide oversight.) The PREP Act thus resulted in umbrella Emergency Use Authorization (EUA) policies for face shields, and manufacturer/device specific EUAs for ventilators, respirators, and surgical masks.

On March 18th, the President invoked the Defense Production Act (DPA) which had the potential to unlock additional federal funding and legally compel American companies to begin producing PPE, ventilators, and other medical supplies. A contingency plan had circulated within the Administration in mid-January, well before the onset of the crisis in the US, that the government would be prepared to use the DPA if necessary. Yet by March 29th, the Administration signaled that it would *not* use the powers of the DPA to begin producing critical equipment, causing “bedlam” in the national PPE market (Nicas 2020). On the same day, the leader of the Federal Emergency Management Agency (FEMA) announced that he was completely “blind to where all the product is” and warned of a dangerous situation emerging in which states would compete with each other to procure already existing PPE stockpiles (ibid). It was not until April 11 when the Department of Defense received White House approval to utilize the DPA to order 39 million masks from 3M, Honeywell International, and Owens & Minor Halyard (Department of Defense 2020).

The COVID-19 pandemic and resulting economic crisis has emerged as a critical test of state-level ecosystems and their ability to mobilize toward common production goals. The infection control procedures required both in clinical sites and non-clinical emergency services (police, fire departments, etc.) required an aggressive expansion of PPE usage– at the same time as consumer stockpiling of PPE magnified the country’s acute shortage. Even if infection rates had remained low instead of growing exponentially, PPE consumption would still have increased dramatically due to the need for intensive infection control procedures.

The rapid increase in demand for testing kits, swabs, ventilators, medical equipment, and PPE such as masks, gloves, face-shields, and gowns, together with the destabilizing effect of the virus on the supply chains normally relied upon by the US healthcare system, created major disruptions in PPE markets. Shortages of PPE threatened the capacity of hospitals to provide treatment for infected patients and to protect their own healthcare workers in doing so.

State governments were thus confronted with a critical shortage of PPE and could not rely on the federal government to directly intervene and produce it. In response, some state governments, including Massachusetts, stepped up and initiated their own PPE production strategies. In doing so, these state governments had to marshal the resources available within their own states and establish new local supply chains that had not previously been geared toward PPE. State-level PPE production has thus been a key test of the strength and flexibility of state ecosystems. Efforts to initiate and ramp up PPE production were met with a series of barriers, each of which could be overcome only with careful coordination among state governments and supportive ecosystem institutions.

A. The Launching of M-ERT

In the context of federal inaction and general confusion around PPE production, the Massachusetts state government mobilized the state's manufacturing ecosystem to generate its own supply-side response to the crisis. Through the existing leadership of the Advanced Manufacturing Collaborative (AMC), which is managed by the state's quasi-public economic development agency, the Mass Tech Collaborative, the Manufacturing Emergency Response Team (M-ERT) was created and held its first meeting on March 20, 2020 to determine how best to help Massachusetts manufacturers pivot production toward PPE. The M-ERT timeline is depicted in Figure 3.

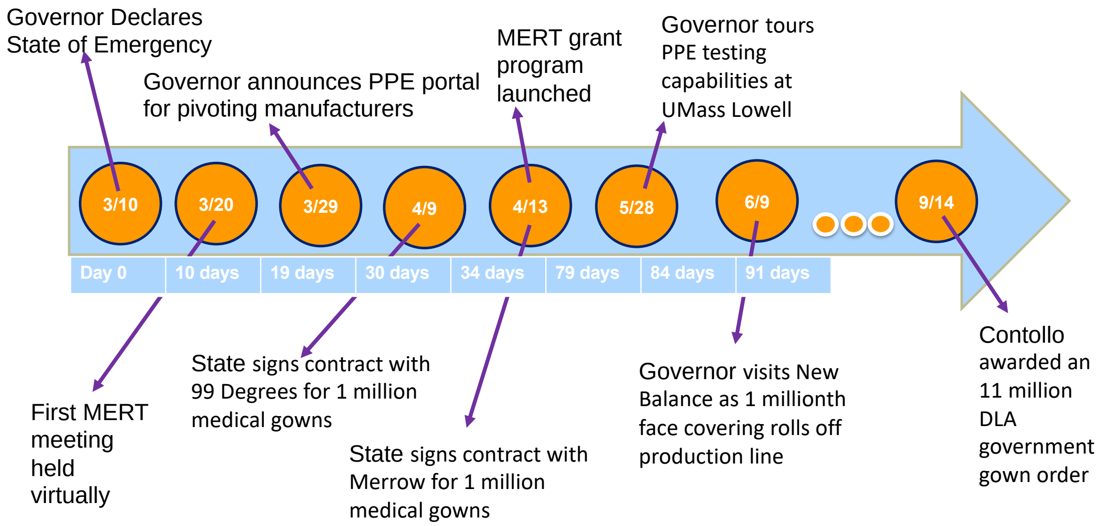

Figure 3: Timeline of key M-ERT milestones, via MassTech Collaborative

M-ERT convened leading experts from universities, healthcare centers, the medical device industry, and manufacturing firms to assist the state's efforts in increasing supply for what at the time seemed like an endless amount of demand. The M-ERT core group quickly brought together representatives from a diversity of institutions: MIT and MIT Lincoln Labs (an arms-length Department of Defense research center), the University of Massachusetts-Lowell, Worcester Polytechnic Institute (WPI), AFFOA, MassMEP, Associated Industries of Massachusetts, Massachusetts Life Sciences Center, Beth Israel Deaconess Medical Center, and several other individual industry partners.

Key volunteers from these institutions convened three times each week over Zoom to discuss strategy for scaling up PPE production within the state. Core team and product leads also communicated more frequently via Slack. The group, chaired by the state's Secretary of Housing and Economic Development, started with 20 invited participants, many drawn from the AMC membership, and soon grew to about 50 as it became clear what kind of expertise was needed in the group or members brought in additional colleagues from their own teams. In Figure 4, the left chart shows the affiliations of the 39 core members, and the right chart provides a detailed breakdown for representatives from academic and R&D institutions.

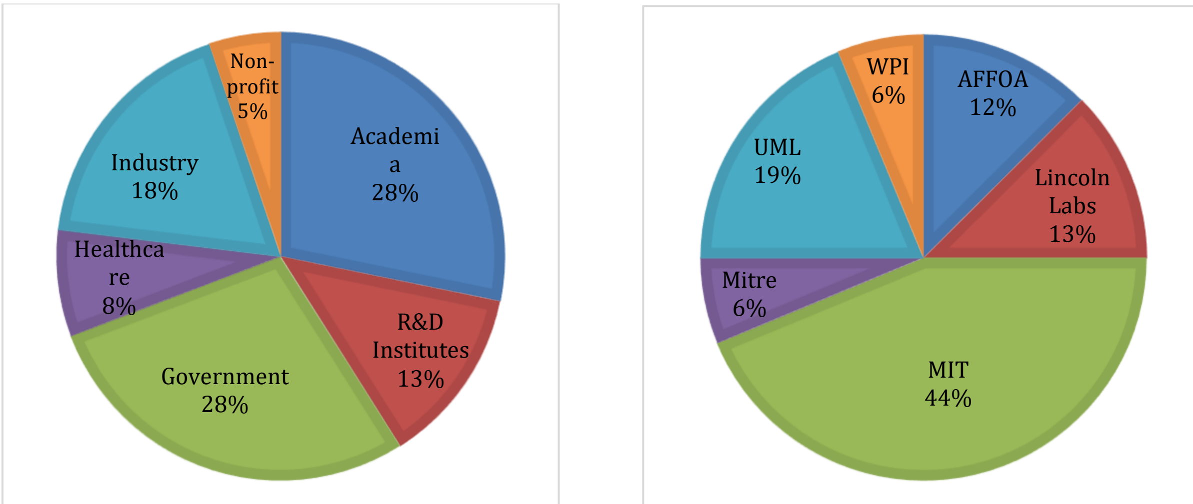

Figure 4: On left, breakdown of M-ERT core team affiliations across 39 core members. On right, M-ERT core team affiliations across the subset of members from academia and R&D institutions.

B. Tapping into the Ecosystem

In mobilizing this interdisciplinary collaborative, several of the organizers agree that the most important feature was the set of pre-existing relationships between companies, the state, and manufacturers– especially the individual people embedded in these ecosystem institutions at the executives of firms. The M-ERT's clarity of mission from the outset, and its grounding in an advanced manufacturing base with the capacity and capability to produce at scale, were critical for immediately attracting buy-in from new partners as M-ERT began its outreach.

The recent innovation investments mentioned above led to three aspects of the Massachusetts manufacturing ecosystem that M-ERT was effectively able to harness during the crisis: (1) pre-existing *organizational infrastructure* and established trust that could rapidly mobilize a collaborative, state-wide effort, (2) an existing *network* of manufacturing institutions and knowledgeable individuals provided critical connections across industry, research, healthcare, and government and, (3) pre-existing *funding* through state programs and institutions that could be pivoted quickly to support PPE production.

Organizational Infrastructure

One critical factor that helps explain the state's rapid response to COVID is the organizational infrastructure that existed in the state that provided both coordination as well as capabilities at the outset of the pandemic. Of particular help was the prior existence of a state-wide manufacturing advisory committee, the Advanced Manufacturing Collaborative (AMC). The AMC, overseen by the Mass Tech Collaborative, provided an organizing body that the Governor's office could turn to as a *de facto* central node for the M-ERT program. This pre-established trust in the state by the manufacturers and in the manufacturers by the state was a critical starting place for the M-ERT. Not only was the state in a position to reach out to manufacturers, but many manufacturers were able to reach out to the state proactively, giving M-ERT a head start with many early pivoting manufactures. In the words of Brenna Schneider, CEO of pivoting apparel company 99 Degrees: "Both [open collaboration and speed] were enabled because the M-ERT leadership was already known to manufacturers in the state. There was already an innate sense of trust and a previously laid groundwork for collaboration and innovation… That network is the very reason that we were able to respond so quickly. Normally it takes 6-18 months to develop a new product. In this case, it has taken three weeks" (Schneider 2020).

Though the M-ERT quickly became a collaborative effort between the AMC and organizations not directly linked to the state government, the effort was started and managed by the state. Having these resources in place likely sped up the M-ERT organization effort dramatically. As one of the participants said, "The AMC was critical… it gave M-ERT the leverage and established an existing structure at the state level." The AMC and the leadership of the Mass Tech Collaborative's advanced manufacturing team facilitated the key networking that needed to take place quickly across the state to engage multiple stakeholders from academia and industry.

It is interesting to note that the organizations involved were a mix of well established, long-standing institutions as well as newer ones highlighted earlier. The Massachusetts Extension Partnership (MEP), played a critical role in vetting the hundreds of small and medium-size companies that submitted their details to the M-ERT portal to potentially support PPE production. The centralization of regional workforce boards under MassHire also helped to facilitate a M-ERT network across the state. MassHire directed all firms interested in PPE production to the M-ERT and also supported firms in implementing COVID-19 safety measures within their factories, including providing online trainings. AFFOA, highlighted earlier, was central to materials sourcing, testing and helping pivoting mask manufactures submit their data to NIOSH and the FDA. MIT Lincoln Labs, the Federally Funded Research Development Center (FFRDC) sponsored by the Department of Defense, also provided some testing capabilities as well as developed rigorous modeling of PPE demand in the state into 2021.

Networks

A pre-existing network linking the state with university groups, firms, and other state-adjacent programs was critical to the rapid scale up of M-ERT. In mid-March, just after the Governor declared a state of emergency, Ira Moskowitz, head of the Mass Tech Collaborative's manufacturing efforts (including M2I2), reached out to a number of academic researchers and administrators, including at MIT where two Research staff members were quickly tapped to run three of the four M-ERT working groups (Winn 2020). Housing and Economic Development Secretary Michael Keneally reached out to senior executives at some of the larger firms to quickly determine capacity and willingness to pivot toward PPE production. M-ERT also tapped smaller firms such as 99Degrees, a high performance activewear manufacturing company in Lawrence that pivoted to the production of Level 1 and 2 gowns in the country. Mass Tech executive director Carolyn Kirk acted as a liaison to the Massachusetts Emergency Management Agency (MEMA), the state's central control for response to the pandemic, and was connected with healthcare professionals who could provide insight into PPE needs. At the same time, many manufacturing firms engaged in aspects of PPE production were reaching out to the state to offer their help. As one of the M-ERT coordinators told us, “Having this kind of state infrastructure combined with the pre-existing network was really critical.”

Also critical to the M-ERT’s successful response was the fact that health system stakeholders such as BIDMC and MGB were able to provide up-to-date information about what was happening at the frontline of the response, such as context about what PPE was needed, how it was being used, and what emergency actions their organizations were taking. In addition, the FDA and the CDC acted as second-order external stakeholders by providing M-ERT team leads with up-to-date information on regulations. The head of M-ERT’s Regulatory and Testing team (mentioned below) had a direct line to the FDA, which allowed him to build confidence with manufacturers by clarifying aspects of federal documentation, and providing advance notice on when new documentation would be released.

Funding

The existence of M2I2, a state-managed grant fund which at the time of COVID had already distributed $50 million in grants toward advanced manufacturing, was an important initial source of funding for firms that were able to pivot production toward PPE. The existence of the funds and a pre-approved process for their distribution allowed for a relatively quick deployment of public funds for PPE production purposes by May of 2020. Approximately $14 million was made available in a new grant program, drawing from both the M2I2 programs as well as the state’s Mass Life Science Center. AFFOA, with processes already in place for vetting grant proposals, became the oversight body for distributing grants. As of mid-August, 28 grant applications had been approved out of 88 proposals, with a combined total of $13.6 million in awards (see Appendix for details). The state dedicated an additional $1 million in workforce training grants working through the Commonwealth Corporation, an entity directly focused on workforce development. Any firm applying for M-ERT funding could request up to $80,000 for workforce training, with a cap of $2,000 per employee, to help workers develop skills to produce PPE and meet FDA requirements.

C. The Organization and Priorities of M-ERT

A slew of coordination problems threatened to slow the state-level production of PPE in Massachusetts. For one, manufacturers that could potentially convert to PPE lacked information about which kinds of equipment were needed and in what quantities. Similarly, firms that were interested in producing PPE needed advice on new physical capital investments and protocols, along with COVID-19 safety. Retooling is always a risky and expensive process, and companies were seeking ways to minimize this risk. Finally, and perhaps most importantly, PPE is a highly regulated domain of products, and most devices and equipment used in a hospital setting must comply with Food and Drug Administration (FDA) specifications. Many of the manufacturers that were interested in converting to PPE production had not previously produced medical equipment and had to learn about FDA regulations and compliance under short timelines and with regularly changing protocols. The FDA was issuing new Emergency Use Authorizations and Emergency Enforcement Policies almost daily, confronting the challenges of trying to ensure the use of quality products in the face of unprecedented shortages that put pressure on the FDA to loosen regulations and find ways to shorten timelines for production. The systemic challenges facing medical devices as addressed by M-ERT are depicted in Figure 5.

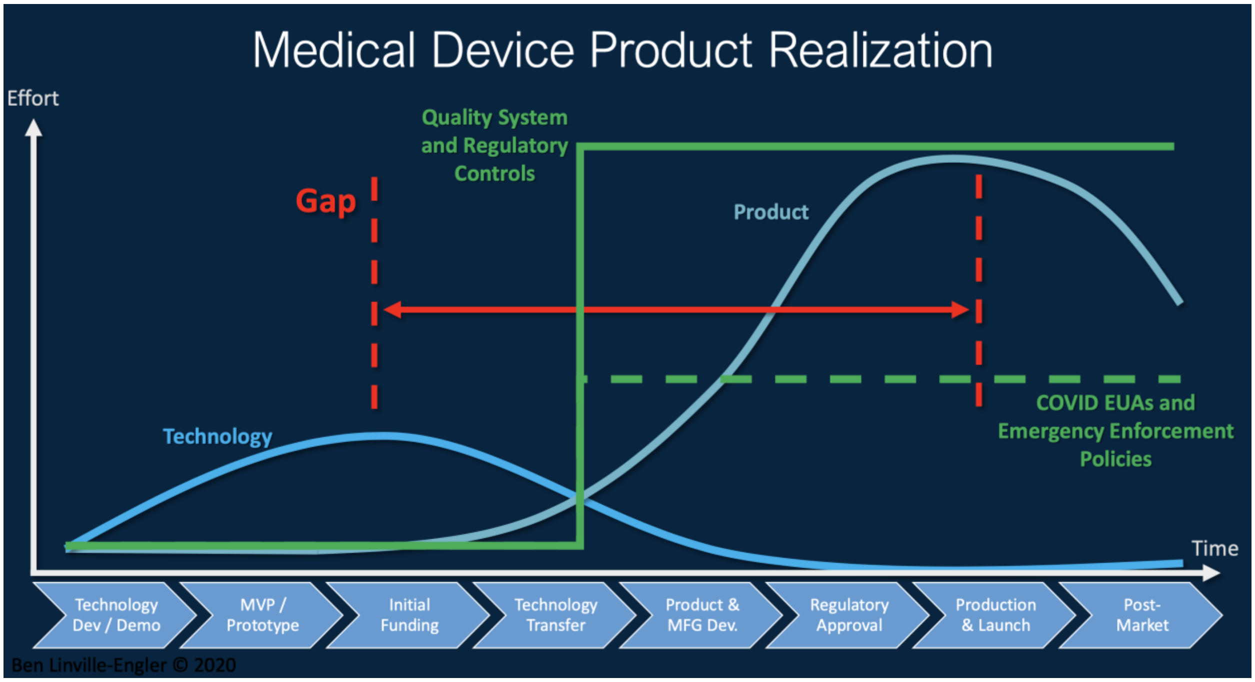

Figure 5: Chart of the barriers and steps facing the development, approval, and deployment of new medical devices during COVID. © Ben Linville-Engler MIT SDM 2020

To tackle all of these barriers simultaneously, the M-ERT was subdivided into four sub-groups with each given a different area of focus:

(1) *Demand* - identifying and quantifying demand in the state; (led by the executive director of Mass Tech, who was the direct lead into MEMA);
(2) *Design Processes* - focused on what specs were required for different types of PPE (led by a representative of MIT);
(3) *Regulatory and Testing* - translating and communicating the rapidly changing policies from FDA to the manufacturing community and state buyers, as well as setting up testing capacity of masks and other PPE (led by representatives of AFFOA, MIT, UMass Lowell and Lincoln Labs); and
(4) *Manufacturing and Supply Chain* – determining manufacturing materials and processes by which PPE could be made, and what capital equipment existed within the state to produce them (led by representatives from MIT and AFFOA).

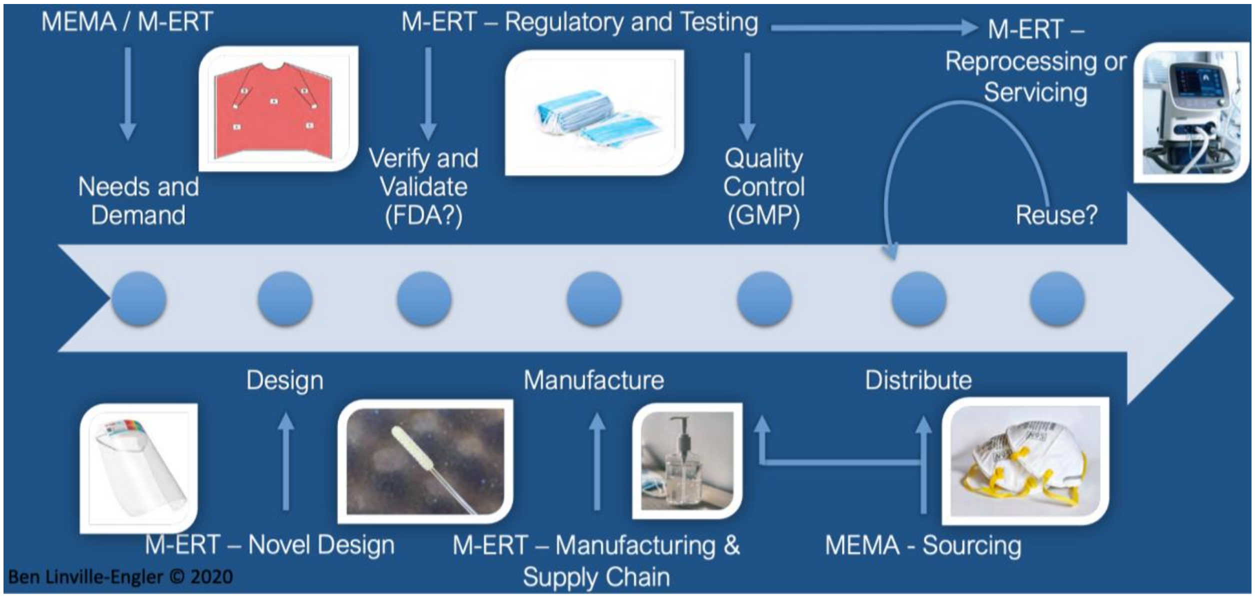

Figure 6: Diagram of M-ERT's total product lifecycle and supply chain initiatives, © Ben Linville-Engler MIT SDM 2020. "Reprocessing or Servicing" refers to a ventilator initiative that was dropped once the team realized ventilator supply was unlikely to be an issue in Massachusetts.

As shown in Figure 6, each sub-group was extremely active with most members of the teams working full time for several weeks fielding queries, determining changing FDA policies, and connecting potential manufacturers with the relevant regulatory and demand-related information. Early on, the decision was made to focus on firms that could meet M-ERT's tripartite framework of "quantity, quality, and timeliness." This led to a focus on larger, more established firms, although a few capable startups (such as Contollo and ViruDefense) were also engaged.

Some important protocols and capabilities were developed in this process. Below provides an overview of how each piece of the M-ERT operated.

1. Demand

Many firms were particularly worried about demand shortages at hospitals, and did not want to over-produce and then find themselves at the end of the crisis sitting on a huge amount of PPE inventory with no potential buyers. At least one MA SME invested hundreds of thousands into pivoting towards face-shield production before realizing that demand had already been met and their new equipment might never pay off. M-ERT also advised a number of enthusiastic larger firms who planned to make face shields that they should focus their efforts elsewhere.

The Demand sub-group interfaced with hospitals and healthcare providers to keep track of the existing demand for PPE. Bringing together stakeholders across the PPE supply chain led to critical and timely demand-side insights. Leading medical experts from the Beth Israel Hospital provided real time information regarding what *kinds* of PPE, swabs, ventilators, and other medical supplies were most critical, in addition to the number of products required. For example, M-ERT manufacturing representatives initially focused on advanced Level-3 gowns because that was the only product that State

Procurement would commit to buying. Once M-ERT medical experts made clear that Level 2 gowns provided sufficient protection, the state relaxed their position and agreed to purchase the lower-level gowns.

Information about quantities and product specifications were relayed to manufacturers in the state. The state government itself helped address the demand problem by initially stepping up as a buyer of PPE and guaranteeing a stream of demand – although, as mentioned later, the state could not guarantee enough reliable demand to assuage the fears of some pivoting manufacturers. M-ERT also worked with the Commonwealth to allow manufacturers that signed up through the M-ERT online portal to officially become categorized as a Massachusetts State manufacturer, which provided a shortcut for those firms to bid on state PPE contracts instead of trudging through an additional registration and evaluation process.

The Demand team also assessed the amount of PPE and other materials that would be needed throughout Massachusetts in the coming 6, 12, and 18 months with help from demand modelling experts at Lincoln Labs. The estimated demand through 2021 for PPE for the state's first responders - those treating COVID-19 patients, those treating others in the healthcare system, and policemen, firemen and EMTs - was enormous: MIT Lincoln Labs estimated up to 54k surgical masks and 928k pairs of gloves per day within hospitals, and up to 1.38M surgical masks and 1.42M pairs of gloves per day for out-of-hospital emergency/healthcare needs. This, combined with increasing cases across the country, confirmed that longer-term solutions would need to be found to ensure that local producers will continue to manufacture enough to supply the country's needs over the next year or more. The Commonwealth of Massachusetts did purchase 3M gowns and some other PPE from local manufacturers, but such state purchases were minimal compared to the actual amount of PPE required– as discussed in the Challenges section below. A potential consortia model for the region among large and small healthcare providers is actively being explored.

2. Design Processes

The Design Process team developed product specifications for a variety of PPE, and evaluated new designs and products proposed by manufacturing firms. See Table 2 for an example specification document the Design Processes team put together for grassroots innovators and/or manufacturers to "articulate their products accurately without marketing hyperbole," so M-ERT could effectively communicate the status and needs of products.

Table 2: Project Specification example from "MASKproject," by Haden Quinlan (template) and Nick Mozer (MASKproject)

Project Scope	The problem is the immediate and worsening shortage of N95 respirators, the strategy is to develop a filter agnostic platform for a variety of filtration materials.
Design Criteria	• Filter media agnostic meeting N95 spec, attached with common materials • Face fit for pressure using common materials, OSHA qualitative testing • Ability to change filter media easily without contaminating mask • Able to be sterilized with bleach, IPA or heat. • Comfortable for at least 3 hours of use • Due to the shortage of filtration media itself, we plan to test a variety of filters for particle pass through.

Image	
Design Approach	• Injection molded with minimal design features for successful first mold. • Common materials for attachment (rubber bands, clamps, etc.) • Straps for pressure for face fit.
Testing and Validation	The testing that is being done and that needs to be done for MVP is as follows: • OSHA Fit qualitative test; (during field test) • NIOSH breathability test (via certified lab) • Aerosols particle test (will provide protocol) In order to move into the field the above tests will need to pass the appropriate FDA regulated tests to show that they are safe for the user. In addition, all QA/QC, manufacturing guidelines and RA documentation will be in order and discussions actively happening with the FDA and support indicated in writing.
Current Needs	1. Legal and liability assistance 2. Design validation and testing 3. Fundraising assistance 4. Manufacturing assistance 5. Coordinating delivery of masks to high-need facilities 6. Warehousing and assembly assistance

A major challenge was dealing with some firms' tendency to submit unproven designs and solutions that were not manufacturable or scalable in the response timeline. In the words of one of the M-ERT engineers, many designers and manufacturers were "building a better mousetrap" instead of iterating on tried-and-tested products. Part of the reason was that major existing players were concerned about the long-term effects of sharing their IP and "training up" their future competitors, which pushed these competitors toward new products instead of collaborations. Beyond that, some inventors just wanted to see their own ideas come to fruition. An early M-ERT meeting involved deciding between ten different prototypes for masks, yet the team needed to quickly unify behind a small set of manufacturable designs before they could start coordinating with manufacturers who knew nothing about face-mask production. Thus, the M-ERT's Design Processes team simultaneously worked to create rapid, robust partnerships across companies while encouraging conversations between qualified experts and engineering teams to minimize noise during the design and design-for-manufacturing phases. For example, the team collaborated with the Mass General Brigham Center for COVID Innovation to help assess new products.

It is interesting to note that, for all of the state's innovation capacity, new and innovative products were not what were needed at this critical point in time. Instead, well-established products and processes were essential to quickly meeting FDA standards and ensuring quality and safety.

3. Regulatory and Testing

Regulatory barriers proved a major complicating factor for those firms that were able to transition to PPE production. The Regulations and Testing sub-group established an open channel of communication with the FDA, CDC, and state government, receiving up-to-the-hour updates on various models for gowns, masks, and other PPE, and ensuring that the manufacturers that had signed on to produce these products could maintain compliance. These discussions between M-ERT members and the FDA allowed the program office to create a data repository with information on various FDA policies and regulations.

There was a tremendous learning curve for many stakeholders, especially buyers and procurement teams, to learn about the intricacies of regulated medical devices and PPE. For example, M-ERT ran into a problem with FEMA and other government buyers around the FDA's vocabulary "approved, cleared, and authorized" which would waive legal liability for manufacturers. Since COVID diagnostic swabs are a Class 1 Exempt device, the FDA had no legal ability to "approve" them – but FEMA was demanding FDA approval before they would submit an order. M-ERT provided a venue for working out these regulatory discrepancies so the factories themselves could focus on manufacturing.

This sub-group also created device-specific buying decision guides for state and health care systems' procurement teams to help them more effectively navigate the changing regulatory landscape, which had an impact on the confidence-level of donated, procured, and imported PPE. M-ERT members became experts on specific product areas and could react quickly to regulatory changes and then advise manufacturers accordingly. M-ERT also formed partnerships with partner institutions to set up in-house testing procedures for certain PPE items.

Testing of domestic and imported equipment - The M-ERT tested over 3,700 individual products for performance requirements. UMass Lowell, MIT (through both the Chemical Engineering Department and Lincoln Labs) and to some extent WPI repurposed existing equipment or ultimately acquired new equipment to provide testing capacity to determine the efficacy of over 100 different brands of N-95, NE-95, and KN-95 masks. This proved important given the number of underperforming masks coming into the state. Analysis by Lincoln Labs and AFFOA found that a full third of the types of masks that the state was receiving for use within hospitals and emergency services did not meet even a 70% threshold for filtration efficiency (the N-95 designation requires a 95% filtration efficiency) – including many brands that been approved in a rush by the CDC and NIOSH under the initial Emergency Use Act, before the CDC realized the extent of labelling and certification forgeries.

Before M-ERT was established, the first wave of mask testing was performed informally in mid-March by an MIT Chemical Engineering professor and two of his graduate students who happened to have the right type of filtration equipment to test masks– although their lab was not certified for N95 evaluation. However, there were only two or three labs in the country who had been approved for certification, and all of them had 6 week waiting times in the early days of the pandemic. In this professor's words, "I saw the NIOSH test and said oh, we can do that… so we just fired up our testing equipment and didn't ask any questions." In the face of overwhelming need, MIT lawyers drafted a release of legal liability overnight. The lab was contacted by hospitals interested in knowing how they could safely sterilize and reuse their PPE without losing filtration efficiency, as well as local fire and police departments whose masks, it turned out, were defective for filtering viral particles. The work of the MIT lab was ultimately transferred by June to UMass Lowell, who used state funds to obtain the TSI-8130a equipment used by NIOSH to test N95s in a standardized setting to conduct confidence testing, which sped up the process of certification for compliant products.

4. Manufacturing and Supply Chain

The manufacturing working group helped determine which manufacturing firms were capable of pivoting and scaling and, if given the green light, directed firms to the requisite specifications for different products.

To identify firms that were viable for pivoting, the MIT sub-team lead developed a quick Google survey to index the states' manufacturing capabilities and capacities. This initial outreach to companies began immediately after the first M-ERT meeting, attracting around 180 responding companies following outreach by MIT, AIM, MassTech, MEP, and other M-ERT partners. Eventually, this survey evolved into a portal through the Mass Tech Collaborative, where interested firms who wanted to pivot toward PPE production could submit their name and qualifications. MassMEP reached out to individual firms to determine their experience and capabilities. Manufacturing firms who were part of M-ERT provided their insight as to how best to help manufacturers quickly pivot and what they might need in terms of assistance.

As soon as M-ERT posted the portal for PPE buyers and sellers, a plethora of companies signed up – providing too much information for the small number of M-ERT team members to meaningfully parse. Many of the manufacturers that had responded to M-ERT's open call were not well-equipped and ultimately not good candidates for firms to make the pivot to PPE. Established firms were best equipped to make the low cost, high throughput, disposable products that were urgently needed by the state– yet many "mom-and-pop" SMEs understandably tried to jump in when the initial call went out as well as startups who had new but untested products.

Triage of these initial requests by the M-ERT team was critical, and this required a significant degree of knowledge about which firms were in the best position to contribute to the effort immediately. Initially, the M-ERT Manufacturing and Supply Chain team and product leads each scoured the response submissions for pivot opportunities, and then MassMEP staff took over to lead SME outreach across the state, with existing MEP field staff targeting familiar firms across various geographical regions. To avoid MassMEP calling every company that submitted, the M-ERT Manufacturing team created a stop-light scorecard for evaluating firms' submissions and quickly weeding out those unprepared to meet their "quality, quantity, and timeliness" criteria.

By the end of M-ERT's first month of operation, over 600 firms had responded to M-ERT's call and filed an application on the online portal, of which roughly 80% had fewer than 100 employees. Only 22% of these firms, however, were deemed by M-ERT as being capable of immediately producing PPE or of quickly switching over production lines to PPE. Several firms after the initial crisis abated have argued that more capacity did exist, but the challenge lay in connecting suppliers into the supply chain of larger firms. For example, when the Manufacturing and Supply Chains team lead hit an impasse with gown production, he brought every company that the team had pre-qualified onto a call together to share their challenges and determine what was needed from the state. Following this initial meeting, some of those companies went off and continued worked together asynchronously – leading to a successful resolution to the manufacturing impasse. Additionally, the existence of a unified message coming from many different voices helped catalyze the state's decision to authorize funding with an initial grant to secure material for gown production, which was then grandfathered into the M2I2 disbursement strategy.

Specific examples of Massachusetts-based firms that have successfully pivoted to PPE production demonstrate these firms' flexibility when supported by the M-ERT and other ecosystem institutions. The advanced fabrics startup 99Degrees Custom worked with M-ERT to retool and switch over its lines to produce Level-1 and Level-2 isolation gowns. Founder and 99Degrees CEO Brenna Schneider recognized that her company's transition to PPE production "cannot be done alone," and that "collaboration, even among competitors, has been one of the most inspiring and authentic parts of [the response]." (Daniels, 2020). By the end of April, 99Degrees had already produced two million gowns that were ready to be deployed in hospitals across the state. Similarly, the sportswear giant New Balance worked with M-ERT and a testing facility at the Massachusetts General Hospital to develop a new facemask out of existing sneaker materials that could be used by hospital workers treating COVID-19 patients. The M-ERT team met with New Balance twice a week for over two months, and the company tested more than five different mask iterations before submitting to a formal lab for certification testing. After developing their mask to increase its level of protection and qualify for the FDA's surgical mask requirements, New Balance ramped up production to over 100,000 masks per week. Merrow, a 100+ year old sewing company in Fall River, also pivoted to PPE production and has now become the largest manufacturer of Level -1 and 2 gowns in the country.

D. M-ERT through the crisis

To date, the M-ERT has helped develop domestically produced supplies of NP swabs, face shields, isolation gowns, face masks, surgical masks, respirators, disinfectants, ventilator components, and sanitizers. By August 2020, M-ERT had connected with more than 900 firms worldwide that were interested in pivoting to PPE production, of which roughly 60% are Massachusetts-based firms from 170 different cities and towns across the state. By November, over 50 companies had collectively produced over 15 million items of PPE for the state with M-ERT support, and three M-ERT grantees alone pledged to produce 28 million N95 masks within their first year of production. See Table 3 for highlighted companies and net PPE production facilitated by M-ERT. In addition, AFFOA tested over 3,700 different types of PPE in total.

Table 3: M-ERT's highlighted companies and production totals as of November 17, 2020

Highlighted Products and Companies	2020 Expected	2021 & Beyond Forecast
Ventilators:		
• Cogmedix - contract manufacturer for Zoll. Worcester	10,000 (Contracted for 10,000)	Volume TBD
N95 Respirators/Masks:		
• Gerson – existing manufacturer that was provided expansion support. Middleboro.	Ramp up	16,300,000
• Boyd Technologies – based in Lee.	Ramp up / 3,000	30,000,000 (annualized)
• Virudefense – surgical mask style for N95. Haverhill.	3,200,000	10,000,000
• Standard Materials/Shawmut – new venture by Fallon family	Ramp up	60,000,000
Isolation Gowns:		
• 99 Degrees – Produced 2 million to date. PO in place with local hospitals for additional 2 million. Lawrence	2,000,000	2,000,000
• Merrow – Sees market reverting to overseas in 2021. Fall River	5,000,000	9,750,000
• Lovepop – Ramping down production. Western MA but manufacturing in Vietnam	2,000,000	TBD
• Contollo – won 12 million unit order from Federal govt. Franklin	100,000	12,000,000
• CareAline – won $25,000 first prize in Mass Tech's Intrapreneur Challenge. Danvers	5,500	100,000
Face Shields:		
• Fraen, FLEXcon, PolymerShapes, Lacerta, Brownmed, Pyxis, Sparx, Lovepop and a few others made a ton, donated much inventory and many had trouble finding buyers.	5,000,000	7,000,000
Other:		
• Boyd Technologies – surgical masks	Ramp up	30,000,000 (annualized)
• Face Masks – New Balance, Lawrence MA. Production ramped down.	1,000,000+	0
• Viral (Kits) / Transport Medium – Mat Tek Corp. Ashland. Selling to Beth Israel, Partner Health and Hospitals in TX and LA	500,000	1,000,000
• PPE Testing – 3,700 tests on PPE have been performed at MIT and UMass Lowell, and facilitated by AFFOA	4,267	1,200
• Hand Sanitizer (approximately 12 companies)	70,000+ gallons	140,000+ gallons
TOTAL PRODUCTIVITY	>15 million items (minus Lovepop)	>170 million items

M-ERT also supported ventilator production (through Cogmedix referenced in Table 3) and repair, although the ventilator shortage turned out not to be as acute as anticipated. Using his MIT connections in California, the M-ERT Manufacturing team lead coordinated a team of engineers with Boston Engineering to ensure that Massachusetts companies were capable of servicing, repairing, and sterilizing old ventilators if necessary.

In calculating workforce and training impacts, Mass Tech Collaborative determined that M-ERT funding led directly to 300 new hires and worker training for 200 people.

Nonetheless, this is only a fraction of the overall estimated PPE demand statewide throughout the pandemic. Despite M-ERT's efforts, less than a third of the state's projected mask needs through August 2021 - 28 million of the estimated 100 million masks - can be made within the state. Of course, no one expects the demand to be met by in-state manufacturers alone, but given the clear identification of demand and the desire by many state manufacturers to participate in PPE production, there is a significant opportunity to meet demand locally.

Still, M-ERT's success has demonstrated the urgency and benefits of recommitting to the industrial commons, as well as the potential for existing state-level institutions to rise to the challenge. To quote AMC Co-chair and SME owner Michael Tamasi: "It's the perfect case study…It's a shame something like this had to happen before you could identify how [manufacturing] affects our livelihoods." Although supply chains and production facilities cannot change overnight, Massachusetts has proven that new manufacturing ecosystem institutions can provide a backbone to support production during a crisis, and that old and new institutions such as MassMEP and AFFOA can play a pivotal role.

One SME ecosystem leader claims that the state of Massachusetts has done more to rebuild the local manufacturing ecosystem in the past few years than the state has done over the past two decades, and the early success of the Commonwealth's COVID-19 production scale-up may vindicate the state's efforts. The same initiatives that have helped firms of every size feel less "home alone" (Berger 2013) were mobilized to rapidly convene, capacitate, and scale up new manufacturing initiatives across the state.

As M-ERT evolves into "M-ERT 2.0," the work of the group will be a more "light-handed" institution offering resource support and facilitating connections within the state's manufacturing ecosystem. The state is largely leaving it up to the marketplace for manufacturers and customers to navigate PPE supply and demand, though efforts to create a regional consortia of sorts are still marching forward.

E. Challenges

For all of its initial success, M-ERT also encountered several challenges that are worth mentioning and reviewing when thinking about lessons learned throughout the crisis.

Lack of reliable demand

Despite M-ERT's successes in catalyzing Massachusetts-based manufacturers for critical PPE production, the state's mobilization efforts did face some headwinds in the process of dealing with the crisis. Even though M-ERT set up as a state entity expecting to sell products to the state, the state lacked the wherewithal to become a substantial source of demand. Within a few months, large firms, with their well-established procurement processes, were successful in obtaining PPE, while smaller hospitals and other care facilities (e.g. elder care) have struggled but offered little in the way of sustained, substantial demand for products. Many firms who were willing to pivot to PPE production but concerned about uncertain demand in the near future were therefore unable to find a large enough market to guarantee profitability. The state government did make some direct purchases, including 3 million gowns and other strategic PPE orders, but did not offer a longer-term source of demand upon which firms could rely (Zeidel, Kirk, and Linville-Engler 2020). In addition to the need for pivoting firms to acquire new machines for PPE production, another area of capital risk was having to commit to consistent material orders (such as melt-blown fabric for N95s) for six months or more. Material inventory was evaporating daily, and the few manufacturers who did secure state order were able to commit to ordering materials in advance at higher volumes, thus guaranteeing their supply and lowering their costs.

Instead, the Commonwealth preferred to play the role of information broker by publicizing those Massachusetts firms that had PPE capabilities so that customers could more easily find them. But in many cases, M-ERT didn't know who actually needed the product, and those needing it didn't know where to buy from. While M-ERT attempted to establish a marketplace to directly connect supply and demand, this turned out to be fraught with legal risk, as public entities are not allowed to preferentially recommend specific products. There may have been some way for the state to make a legal exemption for M-ERT, but the marketplace never materialized. This, according to one of the key M-ERT leaders "was fundamentally the single largest failing of the M-ERT" and left companies to find their own customers.

The challenge of providing guaranteed demand over an extended period of time in the face of uncertainty about a disease is a familiar one in the U.S. A similar challenge arose during the H1N1 crisis in 2009, when manufacturers that ramped up PPE production were left without buyers when the crisis quickly abated (Berzon et al 2020). An alternative model in which the state or, more likely, the national government could provide longer-term contracts is a topic of much discussion and debate as PPE demand remains constant for the foreseeable future; an Executive Order signed in August 2020 aims to maximize domestic production and procurement of goods (including PPE), and reduce dependence on foreign manufacturers (Executive Office of the President 2020).

Product Verification and Price Inflation: In the words of one team lead, "hospitals weren't overjoyed to throw money at unverified products from unknown sellers being touted at a price premium." Hospitals would email M-ERT asking for suppliers, and then complain that M-ERT's newly-pivoting manufacturers were up to 40 times more expensive than foreign supplies pre-pandemic, or they didn't have any literature on their products. Helping pivoting firms prepare medical device product literature and provide coherent documentation on their websites was a significant challenge, and in some cases unsuspecting firms tried to make claims that exposed them to real regulatory risk. This led the Manufacturing team to prepare the product template detailed in Table 2 above.

Labor demand: Some of the manufacturers attempting to pivot had either laid off or furloughed employees due to their lack of demand – and, given the temporarily unemployment bonus, many of these workers were able to earn more money on unemployment and not risk infection by staying home. While these unemployment benefits were a lifeline for many workers who did lose their jobs, the sudden increase in benefits led some low-wage workers to remain on unemployment.

Firm Capabilities and Partnerships within Supply Chains: Despite its connections with firms across the state through the various institutions discussed above, M-ERT still lacked key information about these firms' *capabilities* that would have made the pivoting process easier and more efficient. The M-ERT portal asked firms for their machine types, but couldn't differentiate a small die cutter for prototyping and a wide-area high-throughput machine – creating a need for M-ERT and MassMEP to re-validate supplier capabilities beyond their original submission.

In addition, M-ERT often encountered situations in which firms would have the requisite knowledge to make a portion of certain PPE products, but not the entire products. What was needed was some kind of capabilities database that M-ERT could develop and use in order to match up firms that had complementary capabilities. Without this, M-ERT had to rely on firms' own knowledge of the manufacturing ecosystem, as well as the prior knowledge of M-ERT partners in the ecosystem. As the M-ERT Manufacturing team struggled to find materials for isolation gowns, for example, they serendipitously stumbled across an automotive upholstery fabric firm whose material happened to provide the right liquid barrier protection for gowns. Their FDA contact later introduced them to Dow-Dupont who was working on bulk Tyvek materials for gowns. While it is unrealistic to imagine any organization could have a full understanding of firm manufacturing capabilities, the M-ERT experience underscored how little was really known about which firms were capable of pivoting and scaling.

Partnerships between firms were a challenge. One large original equipment manufacturer declined a M-ERT partnership with other suppliers because they were too busy with their own existing customers, and they were additionally afraid of "training up" their competition or sharing their secret processes knowledge. Inevitably, a small but significant fraction of "volunteer" firms applying through the M-ERT portal were transparently rent-seeking firms looking for a cash infusion from the state . Larger and more capable manufacturers were afraid of partnering with unknown suppliers for fear of signing a contract with this type of firm. In the end, "partnership was not a strong consideration" for M-ERT firms.

Inability to address commodity product shortages

There were two critical products that M-ERT was unable to address: nitrile gloves (mostly made across Asia) and pipette tips for the PCR equipment required for COVID diagnostic tests (mostly made in Switzerland). Both of these are high-volume and low-cost commodities that existing manufacturers have invested large amounts of capital to automate both production and quality control. Nitrile gloves are expected to continue to be in short supply through 2021, and a COVID outbreak at one of the major glove factories in Malaysia in late 2020 threatens to exacerbate the shortage. Both of these products would require a much larger state or federal capital investment than M-ERT'S grants in order to support domestic production.

Overwhelm and burnout

The intensity of the crisis, coupled by confusion within M-ERT on how to organize and devote their attention (especially given the lack of federal guidance), made it very challenging to reflect critically on organizational structure and process efficiency; M-ERT was "building the plane as you're flying it." The team was coordinating efforts seven days a week, preparing for and attending Zoom calls three times a week with dozens of participants, remaining in communication on Slack and GitHub, and regularly working until 3am or later on projects– leading early-stage participants to become overwhelmed. After a few weeks, the two Design team leads realized they had 17 products to manage on their own – so they created product leads for different items to triage their efforts.

By the end of April, many of the key organizers had to leave to take care of their own day jobs and families– leaving an organizational gap when they suddenly left. Also, due to the informality of the initiative, some organizations had temporarily loaned their personnel to the initiative before realizing they needed their people back.

In the beginning, staffing levels at M-ERT led to members of the team becoming "buried" by incoming requests for help and offers of support: as one coordinator said, "We weren't prepared for the total deluge." Initially there were only three M-ERT members fielding potential manufacturing partners– all of whom had other M-ERT responsibilities– and some firms that couldn't reach M-ERT turned to state administration offices which were unprepared for random solicitors. Some key partners thus fell through the cracks, and M-ERT was forced to do "critical damage control" to chase down one upset company who felt they had been ignored despite their robust PPE capabilities. In particular, several out-of-state entities could have been useful for the M-ERT's efforts, yet the initiative wasn't set up to handle firms outside of Massachusetts. Later on, the team managed to set up a few designated, full-time screeners through MassMEP with a specific set of questions and a more polite "no thanks" script for firms that didn't immediately qualify.

External Communication

Despite M-ERT's success, the initiative was under-promoted outside of the state's manufacturing sector – with the exception of an upcoming docuseries created by participating manufacturer Boyd Technologies (Boyd 2020). Yet Massachusetts' manufacturing response, to the knowledge of M-ERT members, has been America's most organized and impactful PPE response by volume. Similar to the hypothesized "Fauci effect" that caused a rise in applications to medical schools (Murphy 2020), M-ERT members hope that sharing their stories can motivate younger people to look at manufacturing as a viable career opportunity, and a way to literally save lives.

VI. Beyond M-ERT: Post-Pandemic Manufacturing Ecosystems

The experience of M-ERT sheds light on the unexpected benefits of investing in and sustaining state-level manufacturing ecosystems in the face of unanticipated crises. But perhaps the larger lesson is the value of building and maintaining manufacturing capabilities in the state– not only for the crises that may arise in the future, but also for the overall health of the economy and future opportunities for strengthening and growing the manufacturing base. Important lessons will be learned from the experience (which a team from M-ERT will be capturing as part of an NSF grant (NSF 2020)). It also underscores the importance of the manufacturing base to the regional economy.

It is worth remembering that almost all manufacturers were deemed essential during the outbreak of the pandemic, and most managed to continue to work through the initial months of the crises, providing economic stability to thousands of workers as well as needed products for the healthcare industry and beyond (NAM 2020). The manufacturing base provides a valuable anchor in the regional economy. But the case also provides an opportunity to reflect on how the Massachusetts manufacturing ecosystem could be strengthened further in order to build and improve upon existing and newfound capabilities and its organizational infrastructure. Massachusetts should not be focused solely on the next viral outbreak. It and other states, with support from the federal government, should continue to invest in their manufacturing ecosystems in ways that help address both acute crises like COVID-19 and longer-term trends, both challenges and opportunities, that may impact the regional industry.

Chief among these today is the potential wave of "deglobalization," in which rising trade barriers and transportation and labor costs may prompt firms to slow offshoring and possibly shift production back into the US. Several post-COVID interviewees mentioned that many American companies have started dual-sourcing their components—rather than sole sourcing from China, as was the case before—to improve their supply chain resilience in the wake of the pandemic. The federal government is actively exploring ways to strengthen domestic manufacturing for critical healthcare supplies. This presents opportunities for growing and expanding manufacturing, particularly in a state that has strengths in medical device manufacturing.

In addition, the benefits of localizing production have become more evident. COVID-19 caused some MA hospitals to rely upon and appreciate their local manufacturers for the first time. At the beginning of the pandemic, a representative from the recently-pivoted textile manufacturer Merrow personally drove some of their PPE samples to a hospital to see whether their supplies met the hospitals' expectations. In the words of one M-ERT coordinator, this personal touch "changed the relationship, instead of just importing PPE from some anonymous foreign supplier"– and the hospital expressed a willingness to work more closely with local firms in the future. For many of these pivoted firms, participating in the medical device industry previously seemed overburdensome or too complicated. While some barriers were temporarily reduced by the FDA during the crisis, closing the gap is not insurmountable, and many of these firms bring new perspectives that could lead to longer term innovation.

Even before the pandemic, interviewees mentioned how Massachusetts firms have begun to realize that reshoring allows for better in-house quality control and a higher degree of process control. The cost of domestic production has also fallen relative to offshoring; in addition to unpredictable U.S. trade tariffs for imported components, labor costs are steadily rising in China and across emerging markets. To take advantage of the potential promise of "reshoring," states will need to restore their institutional ecosystems and ensure that firms can benefit from the industrial commons in order to adapt to the changing production economy.

We suggest that these two ecosystem capacities—short term mobilization and long-term adaptation and planning—are likely to be interdependent and complementary. State-level ecosystems that can effectively respond to acute crises like COVID-19 are also better positioned to benefit from the longer term trends that will affect U.S. industry. As Massachusetts looks to deepen and expand its ecosystem in the near future, it can do so with both types of goals in mind.

While this is only a partial list, we outline here several features of the Massachusetts manufacturing ecosystem that state-level policy makers should choose to emphasize moving forward. Further development of these features will prepare the state for improved responses to the next acute crisis as well as emerging opportunities on the horizon.

A. Strengthening SMEs and Local Supply Chains

Despite SMEs representing over 90% of the state's manufacturing establishments, SMEs still remain largely on the fringes of the Massachusetts manufacturing innovation ecosystem. This is not surprising given that SMEs often lack the knowledge and capacity to invest in new technologies, engage in R&D or participate in state-led programs and policies. However, the role the state's SMEs play in supply chains across multiple industries underscores their importance in the ecosystem. With significant changes ahead to supply chains, whether due to digital technologies or reshoring, positioning SMEs to be more innovative should be a key part of the state's agenda going forward.

Assistance to SMEs has traditionally focused on their incorporation of lean manufacturing practices, a critical "mindset" that all firms benefit from adopting as part of continuous improvement. The MEP has been the lead partner to SMEs in their efforts to "go lean," providing needed guidance, certifications and a range of other services. The next agenda for SMEs is to orient them toward greater innovation capacity in developing new products and investing in new processes that will position them to be more resilient and competitive. New innovators and brokers in the state, such as FORGE, have made important inroads into bringing more SMEs into innovation-oriented work. Others like the Manufacturing USA network broadly, and AFFOA more specifically, have been less focused on SMEs as part of their mission. M2I2 has actively tried to involve more SMEs in its grant giving, but given the design of the program, its reach is limited to those firms already engaged in innovative products and processes and is focused on capital grants rather than funds that can be used to build capabilities.

One of the challenges for SMEs generally with respect to innovative products and processes is the acquisition of new technology. Not surprisingly, manufacturing SMEs lag behind large firms in terms of technology adoption and productivity improvements. As recent research by the MIT Task Force on the Work of the Future demonstrated, SMEs have been relatively slow to adopt some of the productivity-enhancing technologies upon which large manufacturers now rely to streamline processes—robotics, machine learning, smart sensors, and the like (Berger et al. 2020, Armstrong 2020). The problem is primarily one of cost: for SMEs looking to incorporate the latest productivity-improving technology, the capital equipment itself is only a fraction of the overall cost of developing novel products or processes. Tom Ryden, director of MassRobotics, estimates that up to 75% of the cost of a robot is actually installation, including setup and programming which often must be done by integrators or other outside experts. But cost is not the only issue. SMEs often purchase robots for temporary pick-and-place jobs, but once demand for those jobs dry up, these firms lack the internal capacity to repurpose their robots. As Ryden explains, "I've seen so many Fanuc robots just sitting in cages in the corner of firms… the SME will say, 'our robot did its job, and now it's in the corner because we can't reprogram it." Creating new state-level (potentially with federal funding) programs or institutions that could lower integration costs and educate SMEs on how robotics and other technologies could improve their productivity (and importantly how to install and reprogram them), could be an important step toward the technological upgrading of Massachusetts' SME base. This kind of subsidy, unlike capital grants, helps increase manufacturing capabilities while also potentially expanding the local market in an area such as robotics, where there is a strong and emerging cluster of expertise.

Finally, an ability to embrace agile manufacturing (developed in the early 2000s from the software industry) and be more flexible in the face of significant change, whether during the time of a pandemic or otherwise, is an increasingly important quality among manufacturers. While it is not surprising that most of the SMEs that entered the state's portal could not easily pivot operations, it is worth asking what it would take to ensure that more companies could be in a position to take advantage of the opportunity, existing or potential, that might arise with a localization of supply chains.

B. Innovation

Massachusetts innovation capacity is well documented and the COVID-19 crisis only underscored this fact as it relates to manufacturing. Although most of the PPE required by healthcare workers is relatively low-tech, many established firms were quick to develop their own approaches to PPE production (for example, 99 Degrees, Formlabs, and New Balance). Outside of M-ERT, many academic labs and startups developed new product designs within weeks and months of the start of the crisis.

This speaks to the state's innovation capacity, and in particular its robust start up ecosystem, which provides a competitive advantage with few rivals in the country. With the rise of hybrid products employing both software and hardware (e.g., wearables) as well as new digital technologies, the prospect of not just starting companies with production needs in the state but also scaling them has become more plausible. A concerted effort to actively encourage startups to move from prototyping to pilot, demonstration and commercial production in the state should be of high priority for advancing the state's manufacturing agenda. This includes enlisting some of the state's large OEMs to provide beta sites for demonstrations as well as research centers which may be able to make shared R&D equipment available. Both M2I2 and FORGE have made substantial inroads into identifying pathways to help with the scale up efforts of startups with physical products. Other incubators and accelerators, like the Engine, could be valuable partners in such an effort and have been actively advocating for a more robust role for government in growing and scaling such companies in the US (Rae and Carter 2020).

In addition, the state has deep expertise in a number of advanced manufacturing technologies which it should actively cultivate. These include robotics and additive manufacturing, technologies that cut across multiple industries and are just at the beginning of their development lifecycle. Strategic roadmaps should be developed in each of these areas (as has been done by the Manufacturing USA institutes) to outline a plan of action for growth and engagement of the broader manufacturing ecosystem in the state. The state is in the enviable position to not just "make it in Massachusetts" but "deploy it in Massachusetts" as these technologies are adopted by end users. In a recent success story for the state, PRODRIVE, a Dutch electronics manufacturer, opened its US operations in Canton in October, 2020, with plans to employ 150 people. But for the sophisticated robotics and other advanced manufacturing technologies, Prodrive would not be locating in the state due to its prohibitive costs. While the technology makes it feasible, the innovation ecosystem as a whole makes it compelling to companies who are at the frontier of advanced manufacturing.

C. Workforce and Training

All of the above will require a skilled workforce, in many cases with advanced training in the new technologies and production techniques. Pre-pandemic, finding workers was a significant challenge for manufacturers in the Commonwealth. The crisis did not help the situation. Several SMEs interviewed for MIT's Work of the Future research saw their older workers decide to retire early out of COVID-19 health concerns. As mentioned earlier, manufacturing has been less devastated by the pandemic and thus has not laid off thousands of workers. To the contrary, anecdotally, many MA manufacturers have never been busier. Post pandemic, we can expect that the challenge of finding workers, both vocational-level technicians and Bachelor's level engineers, will continue to be a long-term challenge for manufacturers given the aging workforce and lack of high profile for the industry.

Investments by firms in worker skills are often triggered by investments in new equipment (Berger 2020, Armstrong 2020). Another example from an M2I2 grantee highlights the need for additional funds dedicated to training, particularly when it involves an upgrading of technology. A Massachusetts nanotech firm owner who received a M2I2 grant (pre-pandemic) needed to contribute an in-kind cost-share and $600k. He was not able to borrow from local banks, which considered any investment in the firm too risky since the firm couldn't provide enough collateral, and the venture capital climate was not conducive to manufacturing (Reynolds et al 2014). He ultimately borrowed $600k from angel investors to match the state grant. This left him in a challenging position to find additional funding to train personnel on his new equipment, as well as training workers at his lower-tech supplier who also received a new machine. As the firm owner said, "we're going through the school of hard knocks" since none of his workers had any experience with the new equipment and he couldn't afford any additional training staff. He suggested an "M2I2 analogue for human capital" to help transition small firms like his on their technological trajectory. The M-ERT workforce grant, a fund of $1million created to help pivoting firms, could potentially serve as a blueprint for additional training-specific funding for firms engaged with new products or processes, including the introduction of quality control processes and quality assurance at scale. Many of M-ERT's larger firms such as Gillette had robust internal quality processes, but the smaller firms needed significantly more support to meet medical device standards. No doubt the state will also be furthering its investments and learning about manufacturing education and training through the new MassBridge program, which should bring valuable on-line and hybrid learning expertise into the state's workforce training strategy.

While some of our suggestions may require new investments (especially around technological upgrading to SMEs), others can build upon the programs and institutions that the Commonwealth has already established, such as M2I2, FORGE, MassHire, and the longstanding MassMEP, in partnership with the many other private and non-profit manufacturing-related entities. Funding models for these ecosystem institutions is a challenge, with pros and cons to each of the public and private models that exist. Overreliance on the private sector can take ecosystem players off mission, or lead to catering to those with the largest pocket books; under-reliance can make institutions disconnected from the demands of the marketplace. This is worthy of study for the long-term health of the ecosystem and finding opportunities to create synergies across the various stakeholders.

The M-ERT was an impressive example of engaging across the ecosystem, from large to small firm, from academic research center to SME technical advisor. As this paper has outlined, the state's success in mobilizing the manufacturing capabilities within the Commonwealth is directly related to its years of investment in the manufacturing ecosystem. The state's manufacturing ecosystem will emerge from this crisis stronger than before, and all firms, whether successful at pivoting or not, will hopefully benefit from a more robust network of manufacturers and supporting institutions. Now that the Commonwealth has demonstrated its ability to activate its robust manufacturing ecosystem to tackle a short-term crisis, it is time to consider additional statewide investments in long term strategies. With new opportunities on the horizon for additional PPE production, the reshoring of supply chains, and more broadly, the invention and production of new products in the US due to advanced manufacturing technologies, there are many reasons to believe that benefits of investments in the Massachusetts manufacturing ecosystem will continue to pay off into the future.

VII. References

Berger, S. (2006). How We Compete: What Companies Around the World Are Doing to Make It in the Global Economy. Doubleday.

Bonvillian, W. B., and Singer, P. L. (2018). Advanced Manufacturing: The New American Innovation Policies. MIT Press, Cambridge, MA.

Borchers, C. (2020, April 14). How A Factory In Lawrence Went From Athletic Apparel To Medical Gowns. WBUR Bostonomix. Available from https://www.wbur.org/bostonomix/2020/04/14/99degrees-sports-apparel-to-medical-gowns.

Charles, K. K., Hurst, E., & Schwartz, M. (2019). The transformation of manufacturing and the decline in US employment. NBER Macroeconomics Annual, 33(1), 307-372.

Chatterji, A., Glaeser, E., & Kerr, W. (2014). Clusters of entrepreneurship and innovation. Innovation policy and the economy, 14(1), 129-166.

Florida, R. (1999). The role of the university: leveraging talent, not technology. Issues in science and technology, 15(4), 67-73.

Gallagher, M.B. (2020 June 16). Protection on the cheap. MIT Technology Review. Available from https://www.technologyreview.com/2020/06/16/1002965/protection-on-the-cheap/.

Glaser, B. G. and A. L. Strauss (1967). The Discovery of Grounded Theory: Strategies for Qualitative Research. London: Wiedenfeld and Nicholson.

Helper, S. (2011). Challenge And Opportunity In The U.S. Auto Industry: The Key Role Of Suppliers. Economie a Politica Industriale, 38(2), 51–67.

Hill, E. W. (2001). Ohio's Competitive Advantage: Manufacturing Productivity. Urban Publications, Cleveland State University.

Hounshell, D. (1984). From the American System to Mass Production: 1800 to 1932. Johns Hopkins Press.

Inkinen, T., and K. Suorsa (2010). Intermediaries in regional innovation systems: high-technology enterprise survey from Northern Finland. European Planning Studies, 18(2), 169-187.

Massachusetts Technology Collaborative (2020). Manufacturing in Massachusetts. Available from MAmanufacturing.com. Accessed May 2020.

Mokyr, J., C. Vickers, and N.L. Ziebarth (2015). The History of Technological Anxiety and the Future of Economic Growth: Is This Time Different? Journal of Economic Perspectives, 29(3), 31–50. https://doi.org/10.1257/jep.29.3.31

Ohio Manufacturers' Association (2018). "Ohio Manufacturing Counts." Retrieved from http://ohiomfg.com

Pierce, J. R. and Schott, P.K. (2016). The surprisingly swift decline of US manufacturing employment. American Economic Review, 106(7), 1632-62.

Porter, M. E. (2007). Clusters and economic policy: Aligning public policy with the new economics of competition. Institute for Strategy and Competitiveness at Harvard Business School.

Radicic, D., Pugh, G., & Douglas, D. (2020). Promoting cooperation in innovation ecosystems: evidence from European traditional manufacturing SMEs. *Small Business Economics*, *54*(1), 257-283.

Shields, M. (2018). Manufacturing a High-Wage Ohio. The Century Foundation. Available from https://tcf.org/content/report/manufacturing-high-wage-ohio/?session=1&session=1

AFFOA (2020). About AFFOA, available from http://go.affoa.org/how-affoa-works/. Accessed May 2020.

American Manufacturing Communities Collaborative (AMCC) (2020, August 18). Six American Manufacturing Communities Federally Designated for the Defense Industrial Base. Press release, AMCC. Available from https://americanmanufacturingcommunitiescollaboratiev.files.wordpress.com/2020/08/amcc-press-release-dmcsp-8.18.20.pdf Accessed December 2020.

Armstrong, B. (2020). Workforce Challenges On The Factory Floor: A Firm-Level Study Of Human Resource Management At U.S. Manufacturers. MIT Work of the Future working paper, unpublished.

Armstrong, B. B. D. (2019). Brass cities: Innovation policy and local economic transformation. Doctoral dissertation, Massachusetts Institute of Technology. Available from https://dspace.mit.edu/handle/1721.1/122404

Atkinson, R. D. (1991). Innovation policy making in a federalist system: Lessons from the states for US federal innovation policy making. Research Policy, 20(6), 559-577.

Autor, D. H. (2015). Why Are There Still So Many Jobs? The History and Future of Workplace Automation. Journal of Economic Perspectives, 29(3), 3–30.

Baily, M. N., & Bosworth, B. P. (2014). US manufacturing: Understanding its past and its potential future. Journal of Economic Perspectives, 28(1), 3-26.

Berger, S. (2020). Manufacturing in America: A View from the Field. MIT Work of the Future Research Brief. https://workofthefuture.mit.edu/research-post/manufacturing-in-america-a-view-from-the-field/

Berger, S. with the MIT Taskforce on Production in the Innovation Economy (2013). Making in America: From innovation to market. MIT Press.

Berzon, A., M. Evans, S. Stephanie, and A. Hufford. (2020 April 29). "Miscalculation at Every Level Left U.S. Unequipped to Fight Coronavirus," The Wall Street Journal. Available from https://www.wsj.com/articles/miscalculation-at-every-level-left-u-s-unequipped-to-fight-coronavirus-11588170921.

Bonvillian, W. B., & Singer, P. L. (2018). *Advanced Manufacturing: The New American Innovation Policies*. MIT Press, Cambridge MA.

Boyd Technologies (2020). Project Frontline. Docuseries, Boyd Technologies and M-ERT. Available from https://marketing.boydtech.com/en/project-frontline-episode-01-the-crisis Accessed December 2020.

Braczyk, H. J., Cooke, P. N., & Heidenreich, M. (Eds.). (1998). Regional innovation systems: the role of governances in a globalized world. Psychology Press.

Cohen, S. S., and J. Zysman (1987). Manufacturing matters: The myth of the post-industrial economy. Basic Books (AZ).

Commonwealth of Massachusetts (2020). MassHire Department of Career Services. Governor's Budget. Available from https://budget.digital.mass.gov/govbudget/fy20/appropriations/labor-and-workforce-development/career-services/70030800. Accessed October 2020.

Daniels, T. (2020, April 13). Baker Announces $10M Investment for Manufacturers Pivoting to Protective Gear. iBerkshires.com local news. Available from https://www.iberkshires.com/story/62029/Baker-Announces-10M-Investment-for-Manufacturers-Pivoting-to-Protective-Gear.html. Accessed January 2021.

Department of Defense (2020, April 21). Press release, Department of Defense. Available from https://www.defense.gov/Newsroom/Releases/Release/Article/2158351/dod-details-133-million-defense-production-act-title-3-covid-19-project/ Accessed December 2020.

Diop, J. (2017 November 30). MIT's AIM Photonics Academy looks to expand. MIT News. https://news.mit.edu/2017/mit-aim-photonics-academy-looks-to-expand-1130

EARTO European Association of Research and Technology Organization (2015). Knowing your innovation ecosystem actors: data on European RTOs. Available at: http://bit.ly/28Jzfbz

Executive Office of the President (2020 August 14). Combating Public Health Emergencies and Strengthening National Security by Ensuring Essential Medicines, Medical Countermeasures, and Critical Inputs Are Made in the United States. Executive Order 13944. Available from https://www.federalregister.gov/documents/2020/08/14/2020-18012/combating-public-health-emergencies-and-strengthening-national-security-by-ensuring-essential Accessed December 2020.

FORGE (2020). About us, available from https://forgemass.org/about/#mission. Accessed August 2020.

Glasmeier, A. (2000). Manufacturing time: global competition in the watch industry, 1795-2000. Guilford Press.

Gobble, M. M. (2014). Charting the innovation ecosystem. Research-Technology Management, 57(4), 55–59. https://doi.org/10.5437/08956308X5704005.

Hagan, S and Lu, W. (2019, April 16) California is the Most Innovative Economy in America. Bloomberg Economics. Available from https://www.bloomberg.com/news/articles/2019-04-16/california-is-no-1-massachusetts-no-2-in-u-s-innovation-rank

Holdren, J.P. et al. (2012). A National strategic plan for advanced manufacturing. *US National Science and Technology Council,* Executive Office of the President publication, Washington, DC.

ITIF, (2020). The 2020 State New Economy Index. https://itif.org/publications/2020/10/19/2020-state-new-economy-index

Jackson, B.D.J., (2011). What is an innovation ecosystem?, Washington DC. Available from from http://erc-assoc.org/sites/default/files/topics/policy_studies/DJackson_Innovation Ecosystem_03-15-11.pdf .

Klowden, K., J. Lee, & R. Minoli. (2018). State Technology and Science Index 2018. Milken Institute. Available from https://milkeninstitute.org/reports/state-technology-and-science-index-2018.

M2I2. (2020). Grant Awards and Project Details, available from https://m2i2.masstech.org/mass-manufacturing-innovation-initiative/grants-awarded/grant-awards-and-project-details. Accessed September 2020.

Manufacturing USA. (2020). How to Engage with DOD Institutes, available from https://www.manufacturingusa.com/pages/how-engage-dod-institutes. Accessed May 2020.

Markusen, A. (1996). Sticky places in slippery space: a typology of industrial districts. Econ. Geogr. 72 (3), 293–313.

Marshall, A. (1890). Principles of economics. Macmillan. London.
Massachusetts Technology Park Corporation (2019 June 30). Financial Statements and Required Supplementary Information. Available from https://www.mass.gov/doc/masstech-2019-financials/download. Accessed August 2020.
Murphy, B. (2020, December 18). Applications to medical school up big. Is it the "Fauci effect"? Preparing for Medical School blog, American Medical Association. Available from https://www.ama-assn.org/residents-students/preparing-medical-school/applications-medical-school-big-it-fauci-effect Accessed December 2020.
Murray, F., & Budden, P. (2017). A systematic MIT approach for assessing 'innovation-driven entrepreneurship' in ecosystems (iEcosystems). MIT Lab for Innovation Science and Policy working paper. Available from https://innovation.mit.edu/assets/BuddenMurray_Assessing-iEcosystems-Working-Paper_FINAL.pdf . Accessed December 2020.
National Association of Manufacturers (NAM) (2020 September 10). NAM Manufacturers' Outlook Survey Third Quarter 2020. Retrieved from https://www.nam.org/wp-content/uploads/2020/09/NAM-Outlook-Survey-Q3-2020.pdf .
National Science Foundation (NSF) (2020, October 14). FMNet: A Network for Rapid Execution for Scaling Production Of Needed Designs. NSF Awards. Available from https://www.nsf.gov/awardsearch/showAward?AWD_ID=2036917&HistoricalAwards=false
Nicas, J. (2020, April 3). It's bedlam in the mask market, as profiteers out-hustle good Samaritans. New York Times.
OECD. (2018). Oslo Manual 2018, available from https://www.oecd.org/sti/inno/oslo-manual-2018-info.pdf.
Pisano, G. P., & Shih, W. C. (2012). *Producing prosperity: Why America needs a manufacturing renaissance*. Harvard Business Press, Cambridge MA.
President's Council of Advisors on Science and Technology (PCAST). (2011). Report to the President on ensuring American leadership in advanced manufacturing. Executive Office of the President. Available from https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.
Rae, K. and Carter, A. (2020 November). Building a 21st-century American Economy: The role of Tough Tech in Ensuring Shared, Sustainable Prosperity. The Engine white paper. Available from https://www.engine.xyz/wp-content/uploads/2020/11/The-Engine-Tough-Tech-Mandate-2020.pdf Accessed January 2021.
Renski, H. (2014). The influence of industry mix on regional new firm formation in the United States. *Regional Studies*, *48*(8), 1353-1370.
Reynolds, E. and Uygun, Y. (2017) "Strengthening Advanced Manufacturing Innovation Ecosystems: The Case of Massachusetts", Technological Forecasting and Social Change, June, https://doi.org/10.1016/j.techfore.2017.06.003
Reynolds, E. B., Samel, H. M., & Lawrence, J. (2014). *Learning by building: complementary assets and the migration of capabilities in US innovative firms* (pp. 81-107). MIT Press, Cambridge MA.
Rosen, E. (2018, 11 September). Teaming Up to Get Workers Ready for Technology of the Future. New York Times. Available from https://www.nytimes.com/2018/09/11/business/training-tech-workers-for-future.html

Scaringella, L., & Radziwon, A. (2018). Innovation, entrepreneurial, knowledge, and business ecosystems: Old wine in new bottles?. *Technological Forecasting and Social Change*, *136*, 59-87.

Schneider, A. (2020, April 13). COVID-19 Update: April 13, 2020. Livestream, MassGovernor Youtube channel. Available from www.youtube.com/watch?t=900&v=IBwqv4R1q4M&feature=youtu.be Accessed December 2020.

Traficonte, D. (2020). Collaboration in the making: Innovation and the state in advanced manufacturing. Columbia Science and Technology Law Review, 21(2), 328-376.

Winn, Z. (2020, June 9). MIT plays key role in statewide effort to produce PPE. MIT News. Available from https://news.mit.edu/2020/massachusetts-emergency-response-ppe-0609 Accessed December 2020.

Zeidel, M. L., Kirk, C., & Linville-Engler, B. (2020). Opening Up New Supply Chains. New England Journal of Medicine, 382(21).

VIII. Appendix

1. Massachusetts Manufacturing Extension Partnership (MassMEP)

Founded by the National Institute of Standards and Technology (NIST), the Manufacturing Extension Partnership National Network (MEP) has been brokering connections between SMEs (firms under 500 employees) and statewide institutions in every state for over 30 years. There are over 400 MEP service locations across the country, with the goal of helping SMEs improve their bottom line, connect to relevant resources, and become more competitive. MEPs have focused primarily on organizing workshops and consulting for SMEs around organizational innovations such as Lean, and associated inventory and production planning strategies. Around 2012, there was a move within NIST to drive SME innovation through the MEPs– yet, according to one MEP representative, no one could precisely define what innovation meant. NIST communicated to all its MEPs that instead of advising firms, they needed to start getting more involved with the technology side, yet there was little guidance on how to go about doing this. In 2017, the MEP network embedded SME specialists from MEPs into Manufacturing USA Institutes across the country, with varying degrees of success.

MassMEP, founded as a non-profit in 1996, serves 8000 SMEs a year on a fee-for-service basis. The average MassMEP partner firm has about 50 employees. In 2014, MassMEP took it upon itself to go beyond Lean without much support from NIST. This was mostly a competitiveness calculation: there were many other organizations that could consult for SMEs on Lean strategies, but few had the in-depth manufacturing knowledge to help these firms grow their businesses more generally. The director of MassMEP “doesn’t want to push manufacturers”– he wants them to call up and ask for specific services and programs. He started adding programs to help statewide SMEs with higher-level management, strategic planning, marketing, and other growth-centered initiatives. When NIST developed a standard for cybersecurity around 2017, MassMEP added a major program in cybersecurity to assist with manufacturers’ general enthusiasm around internet-connected sensors.

Despite a predominant focus on organizational rather than technological improvements, several of Massachusetts's most high-tech initiatives have worked closely with MassMEP since their inception, and interviewees mentioned how they appreciate MassMEP's manufacturing expertise and connections across the state's SME landscape. MassRobotics worked with MassMEP on connecting and supporting SMEs just getting into robotics, especially around applying for grants such as M2I2.

2. M-ERT Development Grants Awarded

Table 4: M-ERT development grants by type, as percent of total grants

Type of Award	**Grant Amount**	**# of Awards**	**% of Total**
Masks	$ 7,207,996.02	6	53%
Gowns	$ 3,237,903.75	5	24%
Ventilators	$ 1,380,269.26	7	10%
Product Testing	$ 630,781.00	2	5%
Testing (Transport Media, Swabs, Machinery)	$ 541,188.00	3	4%
Hand Sanitizer	$ 341,692.17	3	3%
Other (Materials, Supply chain)	$ 257,755.25	2	2%
Grand Total	*$13,597,585.45*	*28*	*100%*