Innovation and Production: Advanced Manufacturing Technologies, Trends and Implications for US Cities and Regions

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Changes in advanced manufacturing technologies as well as the economics of manufacturing have significant implications for the location and spatial organization of production. As firms employ advanced manufacturing technologies to create 'smart' and connected factories, engage in mass customization, further integrate R&D with manufacturing to enhance innovation, rethink their supply chains to shorten lead times, and demand higher skills and talent from a range of disciplines, where and how twenty-first century manufacturing occurs opens up in ways that have been largely inconceivable in the past. Countries and regions globally are investing heavily in advanced manufacturing technologies because of their important link to innovation and economic development more broadly. However, the implications of these trends for urban manufacturing are mixed and uneven. While manufacturing jobs continue to decline and strong market cities lose more industrial land to conversions to residential and tech office use, greater access to manufacturing tools and technologies are reducing barriers to entry and a new generation of entrepreneurs, artisans and students are engaging in manufacturing and creating a range of new 'maker spaces' in cities. At the same time, the changing economics and emphasis on innovation are making manufacturing in cities and metropolitan areas more feasible for firms in regional industry clusters that rely on advanced manufacturing capabilities. Using a case study from the US state of Massachusetts, this paper proposes a new systems approach for thinking about urban manufacturing that blurs geographic boundaries and looks more closely at the manufacturing innovation ecosystem as a whole and how land-use strategies might support this system.

Developments in manufacturing technologies and processes, combined with changing economics of manufacturing in the global economy, are creating new opportunities for the location and spatial configuration of production. As firms engage in mass customization in smaller facilities, rethink the geographic distribution of their supply chains to reduce lead times, better integrate manufacturing with R&D to enhance innovation, and use new advanced manufacturing technologies that require higher skills and more connectivity, the possibilities for where and how twenty-first century manufacturing occurs opens up in ways that have been largely inconceivable in the past. Advanced manufacturing technologies are breathing new life into traditional, declining industries (i.e. textiles), inventing new industries (i.e. medical electronics) and changing the way firms organize and engage in production (i.e. digital manufacturing).

But will advanced manufacturing breathe

new life into cities and metropolitan areas? Overall, manufacturing jobs in developed economies are in decline as international competition increases and automation plays an increasingly important role in production processes. In geographic terms, cities in particular have lost jobs both in absolute terms and also to the wider metropolitan area. This shift is often driven by pressure to convert industrial land for more pressing demands such as 'tech' office space and residential development, as well as a desire by manufacturing firms for easier access to transportation nodes and customers outside the city. At the same time, however, a new generation of entrepreneurs, artisans, and students has emerged that are engaged in manufacturing as hardware and software merge and technology makes industrial design and prototyping more accessible to everyone. This greater access to manufacturing tools and technologies due to reduced barriers to entry as well as new 'makerspaces' are often located in renovated older urban industrial districts and buildings. In addition, as advanced manufacturing encompasses more 'Industry 4.0'[1] methods, increasing demand for higher skilled workers tends to require these jobs be located in and around cities where talent is concentrated.

Despite the structural decline in employment in manufacturing in developed and in many developing countries, manufacturing plays an important role in innovation and economic development. But manufacturing in the future will not look like it did in the past, nor function in the same way as a stepping stone for economic growth. Apart from macroeconomic trends in jobs or microeconomic trends regarding urban industrial land use, the strength and future of manufacturing lies in regional specializations where manufacturing is understood as an enabling part of the larger regional innovation ecosystem. Urban manufacturing in cities and within the broader metropolitan statistical area (MSA) is part of this larger system and includes large manufacturing firms, small and medium size enterprises (SMEs) that operate within regional supply chains and beyond, colleges and universities that provide training and talent, and startups that generate new products and processes. The premise of this paper is that urban manufacturing in the future will be understood and appreciated more for the role it plays within the innovation ecosystem than as part of a job growth or land-use strategy. While the city continues to offer key strategic locational advantages, it is its role as a source of talent and innovation that will drive manufacturing to locate in and near cities.

After reviewing current trends in advanced manufacturing, the paper examines the implications for our city and metropolitan areas using the United States as a case study, specifically Massachusetts, a high-wage, highly innovative state. A new systems approach for thinking about manufacturing is proposed that blurs geographic boundaries and looks more closely at the manufacturing innovation ecosystem as a whole and how land-use strategies might support this system.

The paper is divided into three sections. The first addresses trends in advanced manufacturing and their implications. The second looks at manufacturing in US cities and metropolitan areas. The third introduces a systems approach to understanding urban and regional manufacturing through the use of a case study. A conclusion follows in which I lay out both the opportunities and challenges for urban manufacturing going forward as well as gaps in our knowledge about investments in manufacturing and scale-up processes among startup companies.

Trends in Advanced Manufacturing and Implications

The increasing interest in manufacturing around the world is fundamentally linked to changes in technology that are reconfiguring all aspects of the production process and creating more value. Because of transformative technologies, the possibilities for manufacturing in high-cost locations like the US, Europe and elsewhere have expanded, while manufacturing capabilities around the world, particularly in developing countries, are also increasing.

Advanced manufacturing technologies are not only changing the cost equation of manufacturing but, importantly, becoming integral to the innovation of new products, processes and services (Berger, 2013). These technologies are central to the development of new, more complex products and processes, often 'hybrid' products that combine hardware with software. Examples include wearable medical devices or small batch, customized biopharmaceutical production based on personalized medicine. As stated earlier, these new processes with their emphasis on software and programming require an upgrading of skills.

Advanced manufacturing may also require closer proximity to R&D capabilities to facilitate continuous iterations between research, development and manufacturing (R, D & M). For some companies engaged in new product introduction (NPI), locating manufacturing near R&D capabilities is an important part of their overall innovation strategy. Strong manufacturing capabilities in the US are also a matter of national security as outlined in the Obama administration's President's Council of Advisors in Science and Technology report on advanced manufacturing (PCAST, 2011).

Below I briefly review some of these new technologies and trends to understand how they might affect the built environment as it relates to manufacturing.

Advanced Manufacturing Technologies and Trends

Advanced manufacturing refers to manufacturing that is less susceptible to competition from low-cost locations because either it uses a high degree of information technology (IT) in its products or processes, and/or it employs workers with higher skills, often measured by the number of scientists or engineers (Helper *et al.*, 2012). It is the use of new IT combined with advanced machinery that often defines advanced manufacturing and leads to increasing automation, intelligence, efficiency, and sustainability in manufacturing processes.[2]

A recent study at MIT identified seven key categories of emerging and potential advanced manufacturing technologies (De Weck, 2014). These include:

1. *Nanoengineering of Materials and Surfaces*. Synthesis and structuring of functional and multifunctional materials at the nanoscale and microscale from the ground up; materials do not exist in nature and thus have no direct counterparts in the natural world. Biomedical applications such as implantable stents are enabled by such technology.

2. *Additive and Precision Engineering*. New manufacturing processes that build up macroscopic parts in fibres or layer by layer and achieve complex three-dimensional shapes starting from ingredients in powder or wire form. This allows for 3-D printing and rapid prototyping at a small scale in a range of materials – plastic, metal, concrete. Dental and medical implants are now built using this method.

3. *Robotics and Adaptive Automation*. Innovative design, use, and adaptation of robots and automation equipment in manufacturing that can replace or augment human labour during manufacturing, especially when very high precision is needed, tasks are easily standardized and repeatable, and large forces and torques are required.

4. *Next-Generation Electronics*. Advanced circuits using non-silicon materials, maskless processes and flexible, potentially organic substrates. This allows for the potential of 'printed electronics' on to clothes, paper or other flexible substrates for wearable devices or product packaging.

5. *Continuous Manufacturing of Pharmaceuticals*

and Biomanufacturing. The process of continuous manufacturing of small molecules as well as turning cells and organisms into programmable factories leads to shrinking the size of chemical manufacturing plants by several orders of magnitude. It may also be applied to the case of biofuels.

6. *Design and Management of Supply Chains*. Planning and managing large and distributed networks of suppliers in multi-echelon supply chains that enable flexible, resilient, and increasingly decentralized distribution of components and products. This involves web-based management of manufacturing.

7. *Green Sustainable Manufacturing*. New manufacturing and recovery processes that minimize the use of energy, recycle materials, and reduce waste and emissions. With the scarcity and potential monopolization of some materials (e.g. rare earth elements) as well as environmental concerns, this has become an important lens through which to design manufacturing processes.

Of these seven, additive manufacturing and robotics and adaptive automation have perhaps received the most attention because they are particularly valuable in reducing time to market and costs. Additive manufacturing makes industrial design and prototyping more accessible while robotics and automation can both reduce the labour costs within manufacturing processes and also extend human capabilities. The implications of the latter are prompting significant discussions about the future of work.[3]

The effects of these emerging technologies on manufacturing can be seen in a depiction of traditional and advanced manufacturing. In the past, manufacturing had four primary stages that operated in a linear fashion (figure 1): sourcing raw materials from nature which were then fabricated into parts, assembled, and then delivered as final products.

Today, several new dimensions show how manufacturing is evolving. Raw materials can often be replaced by *material design*, new synthetic materials that are created from scratch. Fabrication and assembly are blurred through the introduction of highly efficient processes and automation in *continuous processing* that allows batch sizes of one. *Bundling* speaks to the ‘product-service-software’ bundle where the product is not just a physical artefact but an integrated solution that involves the bundling of physical products with

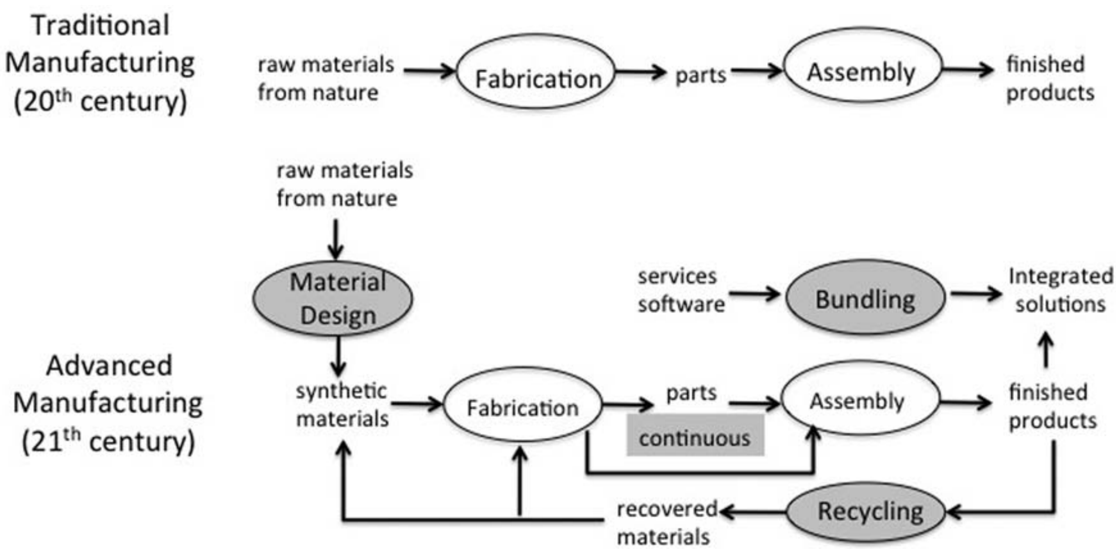

Figure 1. Traditional and advanced manufacturing.

services and software. Finally, *recycling* is a recognition of the problems, environmental and otherwise, with waste and the opportunities for reusing and recycling materials.

Viewed as a whole, the manufacturing process becomes much more complex and non-linear with many more options for reducing time and costs as well as improving quality. The size of the operation can also be reduced to meet smaller scale production goals. Finally, through real and virtual supply chains, the manufacturing process is open to inputs in the form of material design, fabrication, parts and assembly from around the world as well as the cloud.

New possibilities for the production of products and services are being created in established and new emerging industries alike. Even declining industries in the US such as textiles are potentially given new life through breakthroughs in fibre materials and manufacturing processes that will allow fabrics to communicate real-time information, store and convert energy, regulate temperature and monitor health creating a 'fabric revolution'.[4] The potential, for example, of bringing textile production back to older, industrial cities where it has all but disappeared is perhaps a romantic but real possibility.

Supply Chains, Suppliers and Consolidation

There are important changes taking place within the organization of company supply chains which provide the parts, components and assembly that go into delivering a final product to a customer. Whereas OEMs (original equipment manufacturers, typically larger firms) used to be responsible for 80 per cent of the production within the firm and outsource 20 per cent, the 'deverticalization' of most industries has led to the reverse, where firms rely on a large network of suppliers to produce often 80 per cent of their products and services (MIT IPC, 2015). Many of these suppliers are small and medium size manufacturers (with under 500 employees), which represent the vast majority of manufacturing firms in the US. These firms employ over 40 per cent of all manufacturing workers in the US, an increase of 10 per cent over the last three decades (Executive Office of the White House, 2015).

In this model, suppliers become increasingly important as a source of innovation as well as quality control for the lead firm. Some large firms are emphasizing more collaboration with their suppliers to try to collectively find ways to reduce costs and innovate rather than squeeze suppliers for more cost savings (Herrigel, 2010). The emphasis on innovation also increases the value of proximity between suppliers and customers. For those firms engaged in new product introduction, the ability to source parts and iterate with suppliers is key to developing new products in a quality and time-sensitive manner. In highly entrepreneurial and innovative markets like Massachusetts and the Silicon Valley area, proximity to suppliers enhances the 'innovation ecosystem' in the region by allowing innovative firms, large and small, to develop and iterate on new products with suppliers that can provide quick turnaround on early-stage products.

At the same time, OEMs are consolidating their supply chains, reducing the number of suppliers and creating a tiered system that relies on a small number of strategic suppliers at the top of the pyramid, a larger number of bottleneck suppliers in the middle which provide key products and services, and a larger number of 'commodity' suppliers which provide more routine parts and services. Consolidation both within supply chains and across industries more generally is leading to a smaller number of lead firms with fewer companies in their supply chains.

Reshoring Manufacturing

The emphasis on innovation and closer collaboration between upstream R&D and manufacturing explains in part trends in 'reshoring' manufacturing to the US. While it is difficult to track fully, it appears that some companies are reshoring manufacturing and that these activities, combined with foreign direct investment (FDI), are now 'netting out' the offshoring of manufacturing in the US,[5] a significant change in the overall direction of manufacturing job flow overseas over the last decade. An increasing number of firms focused on the US market report that they are reshoring production in order to shorten their supply chains and reduce lead times for products to get from Asia to the US. This allows them to be closer and more responsive to customers as well as reduce shipping costs (BCG, 2015*b*). For some manufacturers, offshoring production to Asia has been less cost effective than predicted due to 'hidden costs' around held inventory, intellectual property concerns and other risks. Such concerns have led to more appreciation for the 'total costs of ownership' that tries to capture all of the costs associated with offshoring production. There have been some high-profile cases of reshoring or new FDI that fuel a belief in a renaissance in manufacturing in the US including: GE appliances' move from China to Louisville; FoxConn's investment in Harrisburg, PA; and domestic and foreign auto investments including Tesla in the San Francisco Bay Area, Volvo in Greenville, South Carolina, and Volkswagen in suburban Chattanooga, Tennessee.

Industry 4.0

These trends in advanced manufacturing can be understood in the context of what has been recently termed the 'Fourth Industrial Revolution' (Schwab, 2016). The Fourth Industrial Revolution builds on three previous stages of industrial development: 1. *mechanization* through water and steam power beginning at the end of the eighteen thcentury; 2. *electrification* that supported mass production started at the end of the nineteenth century; and 3. *automation* realized through information technology and electronics beginning in the 1970s. In this fourth revolution, the previous digital revolution is applied to the physical world, creating *cyber-physical systems* in which 'lines are blurred between the physical, digital, and biological spheres'. From automation, we move to 'autonomization' where machines and products talk to one another creating a vast amount of data that can be analyzed and fed back into the production process to improve performance and productivity.

'Industry 4.0' has become short-hand for the implications of the fourth industrial revolution on networked production systems. Industry 4.0, a term coined by the German government in 2013 and central to German industrial policy, captures the vision and increasing reality of what the digital age means for industrial production. Due to partially or fully automated information gathering and transmission, a virtual copy of the physical world can be created. Cyber-physical systems allow for the collection and processing of data through sensors that then connect to machines, computers, and people, enabling intelligent industrial operations, whether in one factory or across multiple factories and networks around the world that communicate via the internet.

In this kind of production system, multi-product lines can produce 200 different modules with a batch size of one very flexibly. 'The tyranny of bulk'[6] where manufacturing production required large factories and large quantities to achieve economies of scale is potentially replaced by efficient production models for small quantities ('distributed manufacturing'). These 'smart factories' then use data-driven manufacturing intelligence throughout their operations across the entire factory and networks beyond the factory walls.

Such efficient and autonomous production systems make production in higher-cost locations like the US and Europe more feasible. As the Bosch company, one of the founders of Industry 4.0, writes: 'Industry 4.0 offers Germany an historic opportunity to enhance its competitiveness as an industrial location'. Of course, discussion of the autonomization of industrial production systems raises serious concerns about the employment implications of Industry 4.0. Recent analysis predicts that in the next decade, shifts to Industry 4.0 in Germany will increase employment by 6 per cent, but these jobs will require higher skill sets (BCG, 2015*a*). In the short term, greater automation will displace lower-skilled jobs where tasks are more routine or repetitive and even some higher skilled jobs where machines can better analyze data than humans.

While it is challenging to make predictions about future demand for manufactured goods and associated services in any great detail, it is predicted that demand will increase due in part to growing demand in emerging economies such as China and India. It is predicted that consumption in developing economies could increase from $12 trillion annually in 2010 to $30 trillion in 2025. These markets could account for approximately 70 per cent of global demand for manufactured goods (Manyika *et al*., 2013). In addition, the proliferation of new, customized manufactured goods (and the services that go with them) due to the use of new advanced manufacturing technologies will generate additional demand across both developed and developing economies.

Public Policies

These dramatic changes in the way we conceive of manufacturing in the future have led to significant investments in public policies related to manufacturing in the US, Europe as well as China and other parts of the world. In the US, the first PCAST report in 2011, *Ensuring American Leadership in Advanced Manufacturing*, called for the creation of a partnership of government, industry, and academia to identify the critical challenges and opportunities to improve manufacturing across industries. Out of that work the Advanced Manufacturing Partnership (AMP) was created, which has since focused on ways to enable and enhance innovation in manufacturing, build the country's talent pipeline for manufacturing and improve the business environment, particularly as it relates to access to capital (PCAST, 2014). The most significant outcome of this effort was the creation of a network of National Manufacturing Innovation Institutes (NMII). Based loosely on the German Fraunhofer model, the NMII network provides individual institutes federal funds ($70m over 5 years) that must be matched (often by three or four to one) by consortia made up of industry, academia and states to create R&D and cluster-building capacity to solve industry-relevant problems around a specific manufacturing technology such as digital, additive, flexible hybrid electronics, and integrated photonics. While the NMII effort pales in comparison to the investment in advanced manufacturing technologies in Europe and China, it is the most significant investment in manufacturing in the US since the 1980s when the threat of more productive Japanese manufacturers prompted the US to create a national network of manufacturing assistance offices as part of the Manufacturing Extension Partnership (MEP) programme.

As we approach the third decade of the twenty-first century, manufacturing is looking dramatically different from the past. More autonomous production relying on sophisticated technology will require fewer people with higher skills. Manufacturing footprints may be smaller, with increased customization possibilities and more networked and connected relationships within the supply chain. Smaller supply firms will play an increasingly important role in the innovation and production process. Manufacturing processes will become cheaper in general and more accessible to individuals and smaller firms. And for new and emerging industries that require more integration between hardware and software, the connection between R, D & M will be tighter, encouraging greater co-location of the two to facilitate the innovation process.

For these reasons and those summarized above, manufacturing is back in the collective conscious of the US, Europe and emerging economies. A host of factors are transforming the way we think about manufacturing and production more broadly. The question we now turn to is how does this translate on the ground in our cities and metropolitan regions? And how should these jurisdictions respond?

Manufacturing in US Cities and Regions

Despite all these transformative developments in manufacturing, its future in cities is complicated and uneven. Cities and the metropolitan statistical areas (MSAs) of which they are part (home to 80 per cent of all manufacturing jobs in the US (Helper *et al.*, 2012)) vary greatly in terms of manufacturing base, industry specialization and regional economic growth rates, all of which determine the conditions for urban manufacturing. As mentioned earlier, manufacturing jobs nationally have been steadily declining since 2000, but have rebounded post-recession since 2010 along with output and wages (see figure 2). Currently, approximately 9 per cent of the US workforce works in manufacturing (12.5 million workers). Amid the general and steady decline in manufacturing jobs, central cities have lost a higher percentage of these jobs relative to the metropolitan area as a whole (*Ibid.*), with a steady shift of manufacturing jobs from the central city towards inner- and outer-ring suburbs fanning out into the larger MSA. This is due in part to the advantages of exurban locations in terms of generally lower real estate and development costs, easier access to transportation nodes, particularly as truck and air transportation have become more popular, and the increasing importance of distribution centres that are more regionally centralized. In strong regional markets in particular, there is also significant pressure to convert land zoned

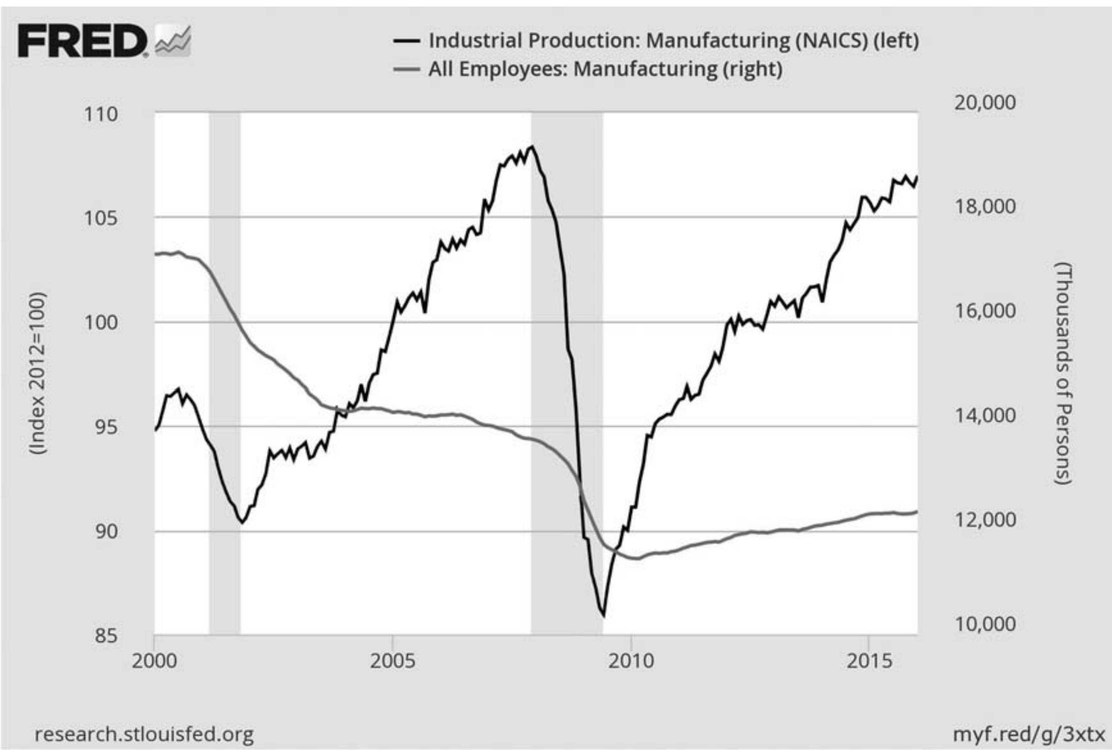

Figure 2. US manufacturing employment and industrial production, 2000 to June 2015.

for industrial use to mixed-use, retail, commercial, office, high-technology, and residential development. Cities including London, England, Vancouver and at least thirty in the US (Chappelle, 2014) are debating the merits of protecting urban industrial land for 'production, distribution and repair' use (PDR). Industrial land has, on the whole, declined significantly in these cities, following the pattern in San Francisco which had 14 per cent of total land area in the city dedicated to industrial use in 1948, but only 4.5 per cent in 2012 (*Ibid*.).

Manufacturing firms in the US are relatively small, with on average sixty employees, and provide higher than average wages compared to all US jobs ($58,000 compared to $47,000). Earnings range widely from over $100,000 for manufacturing jobs in biopharmaceuticals to under $40,000 in textiles. They also require less skilled labour: 65 per cent of all jobs are defined as less than moderately high tech (Helper *et al*., 2012). For these reasons, manufacturing jobs have been seen as valuable to urban economies because they are often more accessible to less educated workers and pay better than average wages.

These firms are part of both 'local clusters' that serve local markets, for example, machinery and fabricated metal products and local food and beverage production, but also 'traded clusters' such as food processing, transportation, and apparel, which can serve regional, national and international markets. Urban manufacturing has historically benefited from competitive advantages that are derived from their central location – proximity to workforce, customers, suppliers and transportation infrastructure nodes (Porter, 2011). As figure 3 shows, most manufacturing industries, including many of those associated with urban manufacturing, have experienced significant job growth between 2010 and 2015 which reflects a cyclical recovery from the Great Recession more than structural forces at play (absolute numbers of jobs are listed on the right, the largest industries in bold). Most have experienced job growth (food and beverage, transportation, fabricated metal and machinery) though there are some that continue to lose employment (textiles, computer and electronics, apparel, and printing and paper) because of international competition as well as significant changes in technology. While some would point to pro-

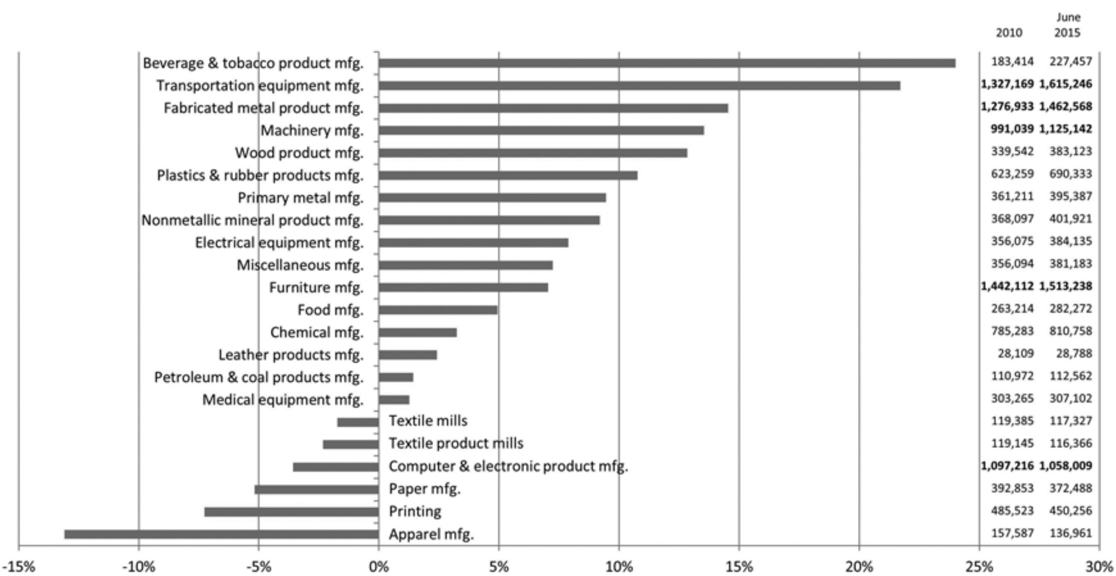

Figure 3. Percentage change in employment in manufacturing industries, 2010 to June 2015.

ductivity gains to explain the job decline in advanced technology products like computers and electronics (an industry that has experienced significant value added over this time period), others emphasize declining US competitiveness and import competition, reflected in the significant gap between imports and exports in such products in the US (Nager and Atkinson, 2015).

These jobs are concentrated in approximately half of the 366 MSAs in the country that have location quotients greater than one (meaning they have a higher than average number of manufacturing jobs relative to the rest of the country). A quarter of MSAs have location quotients greater than 1.5. The automotive, aerospace, energy and electronics industries have been driving strong job growth in many of the MSAs since 2010 particularly in the Midwest (Detroit, Grand Rapids – auto) as well as the South (Louisville – auto) and parts of the West (San Diego – aerospace; Portland, Oregon – semiconductors). Underscoring the unevenness of this bounce back in manufacturing, the largest MSAs for manufacturing, Los Angeles and Chicago, have still experienced a decline in manufacturing jobs during this period due in part to the makeup of their industrial base which includes more traditional industries such as apparel and steel and metal fabrication (Kotkin, 2016).

Geographically, most cities reflect the manufacturing location patterns of Chicago, the second largest urban manufacturing area in the US next to Los Angeles, where manufacturing fans out from the central city towards the inner-ring suburbs and beyond. In the case of Chicago (see figure 4), the central city has 16 per cent of the metropolitan area's manufacturing jobs (a higher than average number), the inner-ring suburbs have 46 per cent and the outer ring suburbs have the remaining 38 per cent (Wial, 2013). The loss of industrial land in the central city has been a contentious issue in Chicago and elsewhere. Chicago has been somewhat effective in protecting industrial land in the city by creating 'planned manufacturing districts' (PMD)[7] first introduced in the city in the late 1980s. Recent research has suggested that these policies have been effective in protecting industrial land in cities despite significant pressures to convert. In the face of these pressures, land-use planning strategies have focused on determining the most valuable industrial land to a city based on criteria linked to economic development indicators such as jobs, and business growth and expansion. Linking to economic development goals and trends, while not the sole criteria for determining the value of PMDs, does help determine which areas are most important to the urban economy.[8]

In the face of this progressive exit of manufacturing from cities, the 'maker movement' and entrepreneurship in hardware-related companies are breathing new life into some urban industrial areas and buildings. The emergence of the maker movement in the early 2000s was the confluence of new, cheaper technology like 3D printing with open-source hardware and an interest among designers, artisans, entrepreneurs and educators to engage

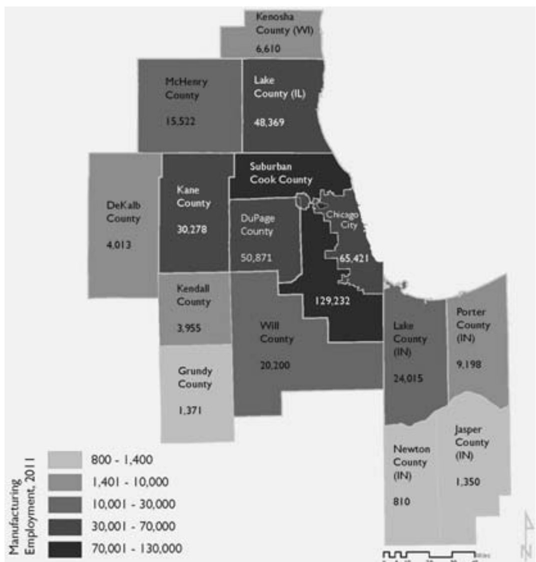

Figure 4. Manufacturing jobs in the City of Chicago and Metropolitan Area, 2011.

in learning-by-doing and custom building while also supporting STEM (science, technology, engineering and math) education (Fallows, 2012). The movement was fostered in part by the creation of FabLabs by MIT Professor Neil Gershenfeld, which made small, mobile fabrication labs accessible to communities in both the developed and developing world. Examples such as Greenpoint Manufacturing and Design Center in New York and American Industrial Center in San Francisco represent large-scale urban redevelopment efforts that support makers. But maker spaces range in size and objectives, from creating space for artisans to 'shop' experience for students to entrepreneurial space for product prototyping. In an example that combines education and entrepreneurship goals, in 2014 General Electric launched FirstBuild, a maker space in the city of Louisville, Kentucky to create the next generation of appliances. This 'microfactory' is in partnership with the University of Louisville and Local Motors, an open source hardware platform.

In cities with a strong entrepreneurial community, maker spaces are more specifically aligned with startup accelerators and incubators that are expanding into prototyping capabilities because manufacturing is integral to the development of new products and services. Boston provides an interesting example of the range of maker-related spaces and partners that have emerged in the past 5 years to support entrepreneurs along a development continuum. MassChallenge, one of the top startup accelerators in the country and now internationally, has created a manufacturing capacity in MADE@MassChallenge, while Greentown Labs, one of the country's largest clean tech accelerators is linking entrepreneurs with local small and medium-size manufacturing enterprises (SMEs) across the state to help with early-stage prototyping, and dedicates almost half of its 95,000 square feet (8,825 m^2) to prototyping.[9] MIT opened its first startup incubator, The Engine, in October 2016 to provide space and resources to startups engaged in 'tough technologies' that require more time, capital and production capabilities to grow.

In addition to these non-profit models, for-profit companies and investors are supporting hardware-oriented startups. Companies like Autodesk, a global computer design company with a focus on construction design, fabrication processes and manufacturing materials, opened a new office in 2016 in Boston's 'innovation district'. BUILD (Building, Innovation Learning and Design) is a 34,000 square feet (3,160 m^2) accelerator space for startups in architecture, engineering and construction industries that provides machinery for prototyping. Singaporean electronics manufacturer Flextronics is following with a 17,000 square foot (1,580 m^2) innovation centre in the same district (encouraged with a multi-million dollar state incentive package) that will be open to startups, universities and more established companies in industries such as robotics, consumer electronics, medical technology, and energy. Both companies have similar operations in the San Francisco area. Bolt, also located in Boston and more recently in San Francisco, bills itself as 'venture capital designed for hardware'. Bolt makes equity investments in hardware startups while providing prototyping space and engineering support as the company develops its product. Bolt's success underscores the increase in venture investment in hardware-based startups which require more time and capital than pure software companies. With the initial public offerings (IPOs) of two tech-oriented hardware companies like GoPro in 2014 (at $6.7 billion) and of FitBit in 2015 (at $8.5 billion), more investors seem to see a future for manufacturing-related companies, particularly those that are consumer-facing.

Once prototyping for startups is completed, piloting capabilities are needed, which often require more space still in proximity to R&D teams but are likely to be located in more exurban locations. The challenge and opportunity for areas like Boston, and high-cost, developed countries in general, is whether, if successful, startups that require manufacturing choose to do more than prototyping and pilot production in the area and expand into commercial production. Historically, much commercial production (and even some pilot) has moved offshore for reasons of both cost and capabilities (Reynolds *et al.*, 2014). Advanced manufacturing technologies and 'Industry 4.0' practices described earlier make commercial production in high-cost locations more of a possibility than ever before, though there is significant international competition from Asia to attract such production, particularly if it is high volume.

These trends capture the varied dynamics of manufacturing within cities: overall, fewer manufacturing jobs and declining industrial space but some limited manufacturing activity in local and traded clusters, as well as signs of new life among a new generation of 'makers' and startup companies that combine hardware and software. When we think about the future of advanced manufacturing and cities, there is much that is in alignment. Manufacturing that has a smaller footprint, using cleaner, more advanced manufacturing processes and requiring higher skills will be more feasible in urban locations particularly when integration with R&D activities is important. Such manufacturing will necessarily locate in and near cities to attract a diverse range of talent and benefit from knowledge spillovers. 'Innovation districts' are providing a new real estate model that can accommodate urban manufacturing, at least at the early stages of development. At the same time, many of the challenging issues for urban manufacturing that exist today will remain – higher costs, congestion, the need for larger industrial space and infrastructure, pressure on industrial land for alternative uses, and competitively priced, more accessible land in inner- and outer-ring suburbs. Many of these challenges will have to be addressed before cities proper see any significant change in recent manufacturing location patterns. Nevertheless, the concept of urban manufacturing has a new generation of champions and examples that rightly place the emphasis on innovation rather than job creation and provide a new vision of manufacturing in cities.

Manufacturing Innovation Ecosystems: The Case of Massachusetts

This uneven landscape for urban manufacturing – macroeconomic trends that suggest overall job decline but strength in certain manufacturing industries; the loss of industrial land, but a new generation of 'makers' and entrepreneurs; and a greater embrace of manufacturing as a whole by business and policy leaders – suggests the need for a new approach to understanding urban manufacturing and manufacturing more broadly. In the end, the strength or weakness of the manufacturing base and its potential for growth in cities and MSAs cannot be understood solely through the lens of macroeconomic trends or urban industrial land zone patterns. Manufacturing must be understood through a 'systems approach' that examines the links between manufacturing and the wider innovation economy. Along with our analyses of industry job growth and decline, industry clusters and land-use patterns, we need to understand the 'manufacturing innovation ecosystem' as a whole, what drives knowledge and innovation within the system and how it can be supported and strengthened within city and MSA economic development strategies, including land-use strategies.

A case study conducted by MIT's Industrial Performance Center (IPC)[10] of manufacturing in Massachusetts and its link to innovative industries underscores this new systems approach focused on the larger manufacturing innovation ecosystem.[11] Massachusetts, with a population of 6.7 million people and some of the country's top universities, is ranked the number one state in the US for science, technology and innovation.[12] Like many regions, its capital, Boston and adjacent city Cambridge, are booming, but many older industrial cities throughout the state struggle with double the unemployment rate of Boston and low educational attainment. Massachusetts presents an interesting window into manufacturing in the US because it is a high-wage location with strong links to the innovation economy. Thus, it must adopt advanced manufacturing technologies to remain both cost-competitive and innovative. Massachusetts is not a major manufacturing state in the US (and it ranks 34th out of 50 for percentage of manufacturing jobs in the state (MIT IPC, 2015)). Manufacturing jobs represent 9 per cent of all employment (approximately 250,000 jobs) with 7,000 establishments, the vast majority of which (over 90 per cent) are small and medium-size manufacturers that employ approximately 30 per cent of all manufacturing workers.

Manufacturing capabilities and advanced manufacturing technologies are integral to several of the state's most important industry clusters including aerospace/defence, semiconductors and computers, biopharmaceuticals, and medical devices. The state competes in manufacturing highly customized products with high 'innovation' content, often the early stage production of new product introductions where quality and time to market are more important than costs. It is also a competitive location for smaller specialized batch production rather than high volume production. Finally, products that benefit from close proximity of R&D with M due to the iterative innovation process and transfer of tacit knowledge are also well positioned as are those that benefit from manufacturing in the country from a regulatory standpoint (e.g. the life sciences).

Given the importance of innovation capacity and high performance among Massachusetts manufacturers, the IPC research examined the sources of knowledge and innovation generation as well as knowledge transfer that support manufacturing within the state. Four key nodes within the manufacturing innovation ecosystem were identified (figure 5): large firms, or original equipment manufacturers (OEMs); SMEs that supply the OEMs and often collaborate with them on new products; startups; and universities. The success of this ecosystem relies in large part on the connectivity between these four nodes. Briefly, the research found that OEMs have the strongest links within the ecosystem because they are largely driving the innovation due to their investments in R&D and need to stay globally competitive. They are also well connected to universities and their R&D capabilities, while also linking to varying degrees with startups that expose

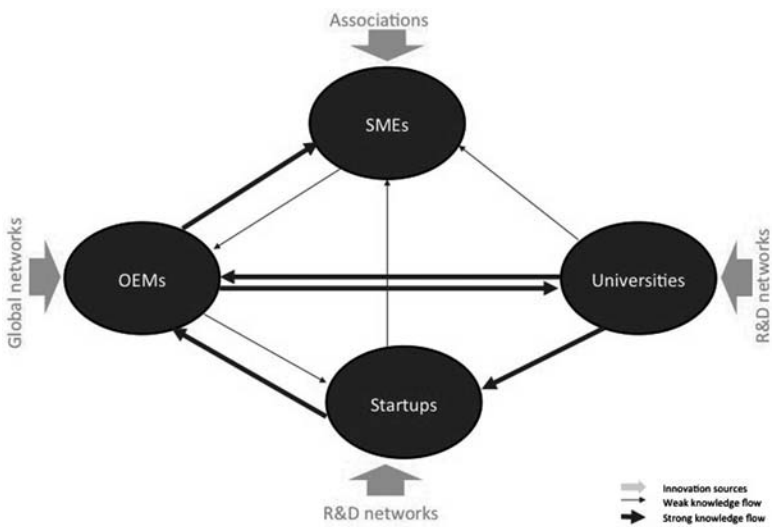

Figure 5. Key nodes in the manufacturing innovation ecosystem.

them to innovative technologies. At the other end of the spectrum, SMEs have the weakest links within the ecosystem. If they are in a 'high road' supply chain, they might be on the receiving end of knowledge and innovation flows from OEMS or collaborators on new products, but this is generally an exception not a rule. Efforts to better connect SMEs with universities have had mixed results because most SMEs lack the time and resources to engage in applied R&D projects while university research timeframes do not align well with the needs of SMEs. SMEs also have weak to nonexistent links to startups. Apart from the strong bilateral relationships universities often have with OEMS, they are tightly linked to startups, which are often born out of the university.

Supporting these nodes in the manufacturing innovation ecosystem and strengthening the links between them requires a strategy that takes a systems approach and involves more connection and collaboration among the four nodes. It can also be supported by land-use strategies that promote this connectivity. When we look at these nodes in the innovation ecosystem through a geographic lens, it suggests the following:

- OEMs (as represented by advanced manufacturing firms) largely occupy some inner- but primarily outer-ring suburbs of Boston;

- SMEs (as represented by precision machine firms) are primarily located in the outer-ring suburbs and in and around older industrial cities;

- Universities are in the city and inner-ring suburbs;

- Startups are primarily in the central city.

Figures 6 and 7 present maps of Massachusetts's OEMs and SMEs respectively, the former represented by what can be considered advanced manufacturing and the latter represented by traditional manufacturing. Each map shows concentrations of firms in specific sub-industries (the larger the circles, the larger the number of firms in that location) that feed into one or more of the broader industry clusters mentioned above. Using several indicators (patents, R&D spend, employment) we identified six of the most advanced manufacturing sub-industries in the state.[13] These are mapped in figure 6 and include navigational and control instruments, semiconductor

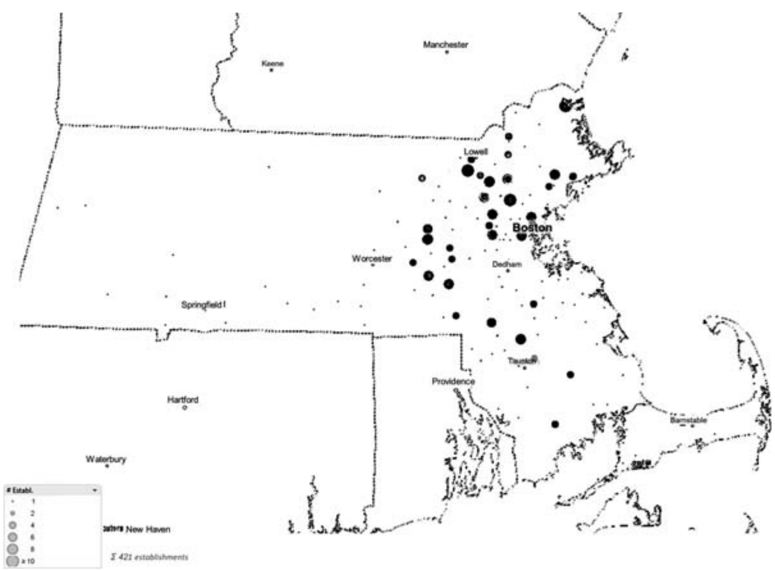

Figure 6. Geography of advanced manufacturing firms in Massachusetts, 2013.

and other electrical components, computer and peripheral equipment, aerospace products and parts, medical equipment and pharmaceuticals and medicines. As the map shows, these firms (just over 400) are largely concentrated in the outer-ring suburbs of Boston with relatively easy access to the central city.

Figure 7 highlights the ubiquity of more traditional machinery manufacturers across Massachusetts. Small precision engineering machine firms represent almost 10 per cent of all manufacturing firms in the state (over 600). These are the backbone of manufacturing because they provide the parts and components that supply the advanced manufacturing industries in figure 6. While largely employing lower skilled workers, these firms are often engaged in very high-end, precision manufacturing with sophisticated just-in-time delivery systems. Though they produce commodity products that could be made in China more cheaply, they are valued for their high quality, quick turn around and responsiveness. As the map shows, these firms are located throughout the metropolitan region with high concentrations in both the outer ring suburbs of Boston and also in and around older industrial cities across the state like Lowell and Springfield. These locations are lower in cost and provide easier access for just-in-time delivery to many of the advanced manufacturing companies.

Seen through this lens, planning priorities emerge for urban manufacturing. These include preserving industrial land in cities for manufacturing that supports key regional industry clusters, while also creating space for the startups, accelerators, incubators and maker spaces that are engaging in early stage manufacturing with SMEs and feeding new ideas and technologies to the OEMs. It also suggests preserving industrial space in inner- and outer-ring suburbs where advanced manufacturing OEMs can locate to benefit from proximity to talent, universities, startups and broad knowledge spillovers generated by the innovation ecosystem.

Two cases in Massachusetts exemplify this last point regarding OEMs. In biotech, an important driver of the Boston economy, core R&D research takes place in the urban core of Boston and Cambridge. The downstream early stage biomanufacturing benefits from co-location because of the complexity of the process and the tacit knowledge exchanged between R, D & M in the early

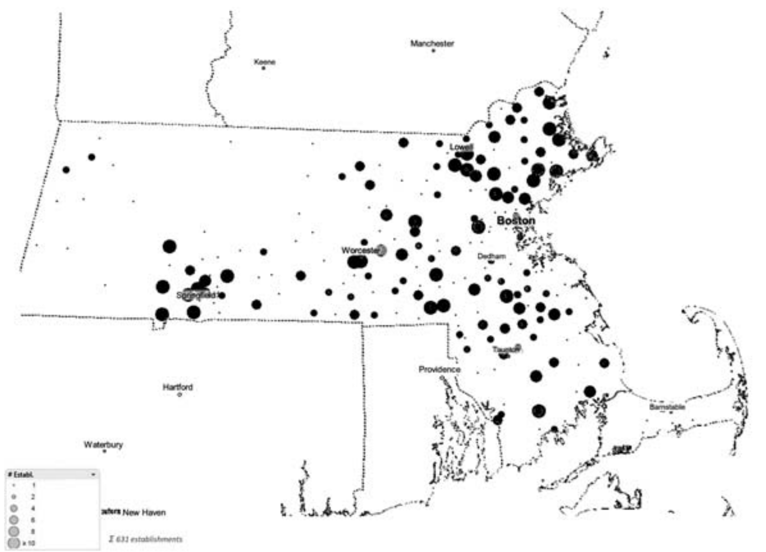

Figure 7. Geography of traditional manufacturers in Massachusetts, 2013.

stages of biomanufacturing scale up. To encourage more of this downstream investment, the regional biomanufacturing trade association created *BioReady Communities*, a programme that guides towns and cities in site development for biomanufacturing.[14] The strategy has been paying off with announcements in 2016 of two biotech firms based in Cambridge each investing \$100 to \$200 million in new biomanufacturing facilities (both 200,000 square feet [18,600 m^2]) within 25 to 40 miles (40 to 65 km) of downtown Boston. In another interesting case, Dutch company Prodrive, is opening its first North American operations in Massachusetts with a 300,000 square foot (27,900 m^2) facility in 2017 in an outer-ring suburb approximately 17 miles (27 km) south of Boston. Prodrive makes a range of electronics products enhanced by an Industry 4.0 vision that employs software and robotics and allows production that would normally be located in Asia to be competitive in a high-cost location like Massachusetts. Prodrive executives cited being near engineering talent as well as to the larger innovation ecosystem in the region as the reasons behind their location decision.

As the Massachusetts case study suggests, new models for manufacturing are bringing investments into cities and their surrounding areas when they are based in advanced manufacturing technologies and innovation. These models provide a pathway forward for reimagining urban manufacturing in the future.

Conclusion

With the advent of new advanced manufacturing technologies, favourable changes in manufacturing cost structures, greater linkages between R, D and M, and supportive public policies, the future of manufacturing in the US looks promising. But as has been emphasized in this paper and elsewhere, it will not look like it has in the past, particularly as it relates to employment. If manufacturing is to succeed in the US and in other developed countries, it will require building new manufacturing capabilities through investments in R&D, technology upgrading among SMEs, the training of incumbent and new workers, and creating a cost competitive environment.

The trends in manufacturing bode well for cities and for metropolitan regions more broadly in terms of its profile (cleaner, potentially smaller footprints) and the emphasis on talent, ideas and knowledge spillovers which established companies seek out and emerging companies are founded upon. Seen from a systems point of view, cities and metropolitan areas have important roles to play to support the regional manufacturing innovation ecosystem through the presence of workers, local and traded industry clusters, universities and colleges for graduates as well as research capabilities, startups and associated maker spaces, and overall facilitation of connectivity within the ecosystem. As some of the examples referred to above suggest, despite a long-term decline in manufacturing jobs, there are signs of growth and investment in particular regional clusters, urban industrial districts as well as older industrial buildings. While not representative of a manufacturing renaissance *per se*, these examples show what is possible and that discussions about urban manufacturing are taking place today within a new framework and context.

With all of this wind at its back, however, urban manufacturing still faces traditional challenges, whether in strong or weak regional economies. In strong regional economies, congestion, infrastructure limitations and competition with alternative uses that have higher market value create formidable challenges for urban manufacturing, while in weaker economies, industrial land assembly and development is often expensive and time consuming. In either case, locations in outer-ring suburbs are often larger, more unencumbered from a development perspective, and more easily connected to distribution and transportation nodes. These realities underscore the value of a systems approach in which urban manufacturing is viewed through the lens of the broader regional innovation ecosystem. From the central city out to the wider metropolitan area, the key nodes within the ecosystem (OEMs, SMEs, universities and startups) should be supported through land-use strategies and other strategies that enhance knowledge flows and connectivity.

Because of the significant and rapid changes occurring in manufacturing, and the difficulty of collecting some data (for example on startups), it is challenging to assess accurately what is happening in cities in manufacturing today in any systematic way. To develop robust analyses of how manufacturing might be evolving in and around cities, manufacturing firms and related assets (such as incubators, maker spaces, universities that engage in manufacturing R&D) should be mapped in terms of the role they play in the innovation ecosystem (scale of firm, industry, advanced or traditional manufacturing). Case studies should be developed in particular of examples of firms that are locating in and around cities. Building a repository of such cases across a range of cities and countries can form the foundation for a taxonomy of urban manufacturing that captures the new dynamics of advanced manufacturing. In addition, while there is significant research and attention spent on startups and entrepreneurial ecosystems, relatively little is known about their process of scale up. Tracking startups' manufacturing strategies as they scale from prototype to pilot to commercial production will shed light on both the land-use requirements of these companies as they grow and the factors that potentially lead startups to manufacture offshore.

Given the changes taking place in manufacturing, future analysis must be concerned not just with jobs and industrial land use, but with the role urban manufacturing plays in the wider innovation economy. With this understanding, urban manufacturing becomes an important component of future city and metropolitan planning and growth strategies.

NOTES

1. Industry 4.0 or the fourth industrial revolution, is the current concept that captures the use of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, the Internet of Things and cloud computing.

2. PCAST defined advanced manufacturing as 'a family of activities that depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences. It involves both new ways to manufacture existing products and the manufacture of new products emerging from new advanced technologies' (PCAST, 2011).

3. To what extent robots replace or enhance labour is a point of discussion. As it stands, labour costs generally do not exceed 20 per cent of total costs in manufacturing and thus are already a relatively small proportion of overall costs. There is little debate, however, that automation is replacing lower-skilled routinized jobs, reducing labour costs in manufacturing further (Siu and Jaimovich, 2015).

4. The Advanced Functional Fabrics of America (AFFOA) was launched in April 2016 as one of the country's National Manufacturing Innovation Institutes (NMII): http://join.affoa.org.

5. The Reshoring Initiative has been tracking these trends to try and move beyond anecdote with respect to reshoring, see http://www.reshorenow.org.

6. This term was coined by Professor Sanjay Sarma at MIT in his contributions to *Making in America* (Berger, 2013).

7. PMDs are defined more broadly than just manufacturing and can include postal services, utilities, building, maintenance services, construction, office and some retail space, warehousing and distribution, and automobile repair.

8. A detailed cost-benefit analysis of industrial land use in inner-ring suburbs of Washington, DC by Howland (2011) shows ways in which industrial land can be categorized based on industrial demand, informing zoning strategies. Chappelle (2014) links industrial land to the ability of businesses in the East Bay sub-region of the San Francisco Bay area to expand.

9. For more about these organizations, see: Greenpoint Manufacturing and Design Center: http://www.gmdconline.org; American Industrial Center:

http://aicproperties.com: GE's FirstBuild: https://firstbuild.com; Bolt: https://www.bolt.io; Made@MassChallenge: http://masschallenge.org/programs/made; and Greentown Labs: http://greentownlabs.org; MIT The Engine: http://www.engine.xyz.

10. More information on the MIT Industrial Performance Center (IPC) can be found at http://ipc.mit.edu.

11. Data and findings in this section can be found in the IPC report, 'Strengthening the Innovation Ecosystem for Advanced Manufacturing: Pathways and Opportunities for Massachusetts' (IPC, 2015) available at: https://ipc.mit.edu/sites/default/files/images/Report.pdf.

12. ITIF 2014 State New Economy Index: https://itif.org/publications/2014/06/11/2014-state-new-economy-index; The Milken Institute, State Technology and Science Index, 2014: http://www.milkeninstitute.org/publications/view/675.

13 These industries were identified at the four-digit NAICS code level (North American Industry Classification System), the most reliable and frequently used source of industry data.

14. BioReady Communities: https://www.massbio.org/why-massachusetts/supercluster/bioready-communities.

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