Trends in Advanced Manufacturing Technology Innovation

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Summary and Goals

This chapter summarizes the trends we observe in technology research and development that relate to the current and future state of advanced manufacturing. We first explain how manufacturing has traditionally been defined and how the processes in a production plant have been viewed as a mainly step-wise linear transformation of inputs towards finished goods. We then provide an expanded definition of "advanced manufacturing" that expands the traditional view in several ways and maps to seven key manufacturing technology categories. Our findings on manufacturing technology innovation are based on a combination of an internal scan of research at MIT, an external survey of U.S. programs in manufacturing and an extensive literature search. Taken together these trends indicate

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that there is much innovation happening in manufacturing technology research, both in universities as well as in industrial firms, and that opportunities for entirely new products and services, further productivity gains and game-changing processes are on the horizon. However, none of these trends are likely to create large numbers of new jobs. However, the jobs that will be created and maintained in advanced 21st century manufacturing require higher levels of skills and a deep understanding of the underlying physics and economics of manufacturing.

The overall goal of this chapter is to find how innovation in manufacturing processes and associated product design impacts the prospects for manufacturing in the early 21st century. While most of our data is based on research at MIT and other U.S. institutions we believe that our findings apply to other industrialized nations as well. Our goal is to find trends and promising areas of manufacturing technology research both at MIT and at other universities and firms. Innovations in manufacturing are often reported one-at-a-time and it is not immediately clear how these innovations fit together and how they collectively impact the practice and economics of manufacturing. We seek to present advanced manufacturing technology innovations in a larger context. In summary, we are looking for potential game-changing approaches to new manufacturing and a clear definition of what is "advanced manufacturing" in the 21st century.

The key results presented in this chapter are as follows:

1. A qualitative and quantitative assessment of 24 manufacturing technology areas in terms of their importance and promise to have a positive effect on manufacturing in the early 21st century. This also includes a discussion of which technologies are universally viewed as promising and which ones are more controversial based on the variances found through our external survey.

2. A suggested grouping of these 24 manufacturing technology areas into seven major categories. We believe that these categories are clearer and more consistent than lists of technologies that have been proposed in some other recent reports on manufacturing.

3. A new definition of what advanced manufacturing is and the role that the seven technology categories play or can play in this expanded view of manufacturing. The seven technology categories are mapped to four major trends that turn manufacturing from a traditionally linear step-wise process to a more integrated and closed-loop enterprise. Based on our interviews we also provide selected examples of how firms leverage new technologies for advanced manufacturing.

4. We summarize the hurdles faced by U.S. academic institutions in advanced manufacturing research and suggest possible models and actions for improvement.

Position of this chapter in the overall PIE study

As discussed elsewhere the Production in the Innovation Economy (PIE) project was inspired by the work of the MIT Commission on Industrial Productivity (1986-89). Early on in our deliberations it became clear that the world is now a more complex and more interconnected place than it was in the 1980s. While the need to grow productivity through process improvements and technology exists today as it did 30 years ago, there are substantial differences. China has displaced Japan as the leading industrial nation in Asia and perhaps the world. Many firms have deverticalized their value chains and are now part of global supply chains that offer new opportunities but also new risks such as supply disruptions, theft of intellectual property and so forth. Many of the large U.S. firms have closed or significantly reduced the size of their R&D departments and rely increasingly on universities and the acquisition of young startup companies as a source of innovation. In short, a deeper understanding of production in the 21st century requires viewing it as a complex system with interlinked factors including innovation, the role of production activities and supporting services, the impact on the labor force as well as the role that regional and federal governments can and should play in creating an ecosystem that will lead to long term economic prosperity.

Figure 1 depicts the role of production in an advanced economy as a complex system. The position of this chapter (labeled as "module 1") on advanced manufacturing technology is at the interface between our innovation system and industrial production.

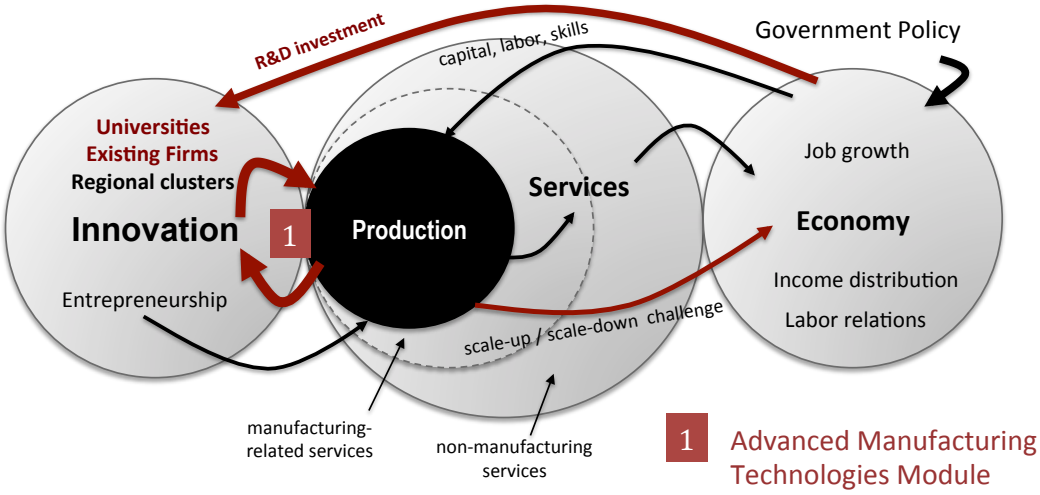


Figure 1: Structure of PIE study and position of the innovation-production interface

Innovation involves important feed-forward and feedback mechanisms in the real economy. The invention of new products and processes, as well as the improvement of existing processes, leads to higher productivity and expansion of product portfolios and associated service offerings. In turn, the experience and insights gained from manufacturing activities at scale often trigger ideas for new innovations at the front-end. One of the main worries about separating R&D from production activities is that this feedback mechanism (see arrow pointing from Production to Innovation in Fig.1) will be

interrupted or dampened. Another mechanism in which innovation impacts the economy is through patenting, licensing and the scale-up of new firms (see chapter on scale-up in this book). Finally, there continues to be an important role for R&D investments by the federal and regional governments to ensure that the pipeline of "radical" long-term innovations remains healthy at the front end. We believe based on our research that if any of these feedforward or feedback mechanisms are disrupted, that it will negatively influence the whole system over time. In contrast to *Made in America* [1] which was a study decomposed by different sectors of the economy (automobiles, chemicals, consumer electronics …) we take a functional view in the PIE project and focus on different functions in the innovation-production system. Functions discussed in other chapters are the scaling up of young firms, education of the workforce and management of collaborations across national boundaries. The function considered in this chapter is that of inventing and improving the next generation of manufacturing processes and products.

Research Approach

We carried out the research on advanced manufacturing technology innovation reported here in the following four steps.

First, we conducted a scan of research happening at MIT by assembling a list of principal investigators (PIs) that are involved in "manufacturing" research. We cast a wide net and included researchers who are innovating in processes for creating new components, artifacts and systems, even when they themselves do not label their research as "manufacturing" or "production" related. This list of 147 PIs was subsequently expanded to 199 individuals based on 30 interviews and laboratory visits carried out between July 2011 and August 2012. This list of PIs also led to the subsequent formation of six manufacturing working groups at MIT that closely mirror the seven technology categories we discuss in this chapter.

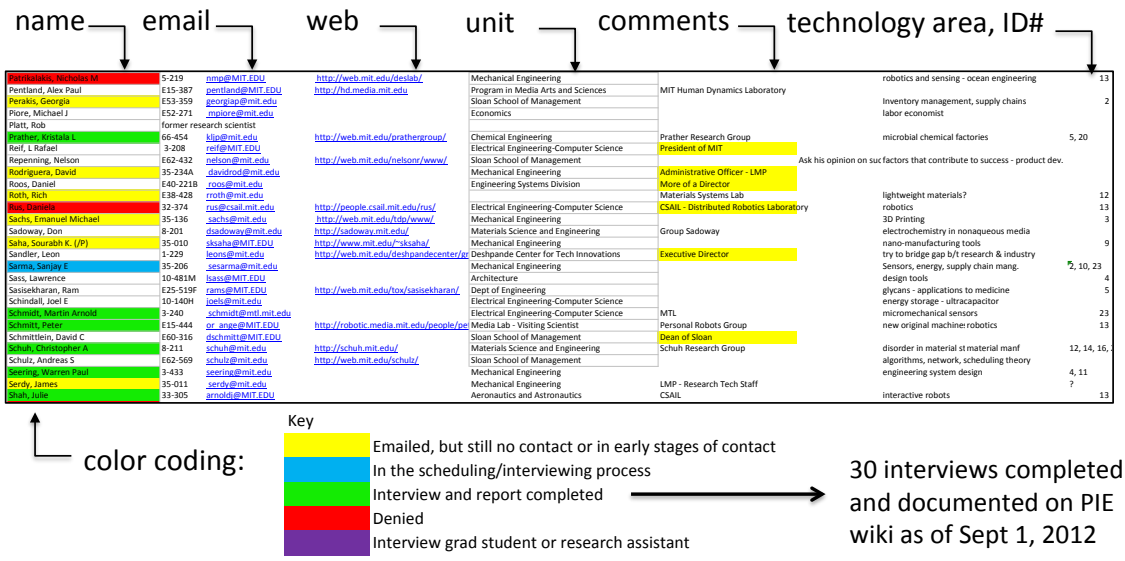
Second, we conducted a survey of 85 U.S. programs in industrial and manufacturing engineering to elicit their views on trends in advanced manufacturing technology research and development. We achieved a response rate of 34% and obtained interesting insights, many of them consistent with the findings from our internal scan at MIT. We also gathered important inputs on what makes manufacturing research challenging in the U.S. and what could be done to improve the U.S. manufacturing research enterprise. One of the key results of this effort was the grouping of advanced manufacturing research into seven distinct technology categories that complement each other. We believe that this grouping is clearer than the lists of manufacturing technology that had been proposed in other recent reports on manufacturing (see cross-comparison with reports on advanced manufacturing by PCAST, AMP, IDA, the U.S. Manufacturing Competitiveness Initiative, and the McKinsey Global Institute). A literature search of about 500 papers on manufacturing technology research published since 2008 showed that U.S. research in advanced manufacturing is active but quite distinct from the kind of research funded directly by industry firms.

Third, we extracted from the 200 interviews conducted as part of the PIE study examples of firms that either develop or leverage innovations in advanced manufacturing to create or gain access to new markets and improve their operations. We map these examples to the seven technology categories.

Finally, we integrated our findings by providing an expanded definition of advanced manufacturing and show how the seven technology categories impact the four major trends that make advanced manufacturing different from traditional manufacturing.

Internal Scan at MIT

We begin our analysis by providing a scan of current manufacturing technology research happening at MIT. Figure 2 shows an excerpt of our approach to identifying principal investigators (PI) at MIT that are involved in manufacturing research. MIT PIs were identified under the broad category "Manufacturing, Design and Product Development". The Office of Institutional Research in the Provost's office compiled this list using a variety of methods. They first performed a key word analysis of websites and subsequently sent the results to individual faculty members to confirm. We subsequently augmented this list with additional non-PI researchers based on our interviews and laboratory visits.



name		email	web	unit	comments		technology area, ID#	
Patrikalakis, Nicholas M	5-219	nmp@MIT.EDU	http://web.mit.edu/deslab/	Mechanical Engineering			robotics and sensing - ocean engineering	13
Pentland, Alex Paul	E15-387	pentland@MIT.EDU	http://hd.media.mit.edu	Program in Media Arts and Sciences	MIT Human Dynamics Laboratory			
Perakis, Georgia	E53-359	georgiap@mit.edu		Sloan School of Management			Inventory management, supply chains	2
Piore, Michael J	E52-271	mpiore@mit.edu		Economics			labor economist	
Platt, Rob	former research scientist							
Prather, Kristala L	66-454	klip@mit.edu	http://web.mit.edu/prathergroup/	Chemical Engineering	Prather Research Group		microbial chemical factories	5, 20
Reif, L Rafael	3-208	reif@MIT.EDU		Electrical Engineering-Computer Science	President of MIT			
Repenning, Nelson	E62-432	nelson@mit.edu	http://web.mit.edu/nelsonr/www/	Sloan School of Management		Ask his opinion on suc	factors that contribute to success - product dev.	
Rodriguera, David	35-234A	davidrod@mit.edu		Mechanical Engineering	Administrative Officer - LMP			
Roos, Daniel	E40-221B	roos@mit.edu		Engineering Systems Division	More of a Director			
Roth, Rich	E38-428	rroth@mit.edu			Materials Systems Lab		lightweight materials?	12
Rus, Daniela	32-374	rus@csail.mit.edu	http://people.csail.mit.edu/rus/	Electrical Engineering-Computer Science	CSAIL - Distributed Robotics Laboratory		robotics	13
Sachs, Emanuel Michael	35-136	sachs@mit.edu	http://web.mit.edu/tdp/www/	Mechanical Engineering			3D Printing	3
Sadoway, Don	8-201	dsadoway@mit.edu	http://sadoway.mit.edu/	Materials Science and Engineering	Group Sadoway		electrochemistry in nonaqueous media	
Saha, Sourabh K. (/P)	35-010	sksaha@MIT.EDU	http://www.mit.edu/~sksaha/	Mechanical Engineering			nano-manufacturing tools	9
Sandler, Leon	1-229	leons@mit.edu	http://web.mit.edu/deshpandecenter/pr	Deshpande Center for Tech Innovations	Executive Director		try to bridge gap b/t research & industry	
Sarma, Sanjay E	35-206	sesarma@mit.edu		Mechanical Engineering			Sensors, energy, supply chain mang.	2, 10, 23
Sass, Lawrence	10-481M	lsass@MIT.EDU		Architecture			design tools	4
Sasisekharan, Ram	E25-519F	rams@MIT.EDU	http://web.mit.edu/tox/sasisekharan/	Dept of Engineering			glycans - applications to medicine	5
Schindall, Joel E	10-140H	joels@mit.edu		Electrical Engineering-Computer Science			energy storage - ultracapacitor	
Schmidt, Martin Arnold	3-240	schmidt@mtl.mit.edu		Electrical Engineering-Computer Science	MTL		micromechanical sensors	23
Schmitt, Peter	E15-444	or_ange@MIT.EDU	http://robotic.media.mit.edu/people/pe	Media Lab - Visiting Scientist	Personal Robots Group		new original machine robotics	13
Schmittlein, David C	E60-316	dschmitt@MIT.EDU		Sloan School of Management	Dean of Sloan			
Schuh, Christopher A	8-211	schuh@mit.edu	http://schuh.mit.edu/	Materials Science and Engineering	Schuh Research Group		disorder in material st material manf	12, 14, 16,
Schulz, Andreas S	E62-569	schulz@mit.edu	http://web.mit.edu/schulz/	Sloan School of Management			algorithms, network, scheduling theory	
Seering, Warren Paul	3-433	seering@mit.edu		Mechanical Engineering			engineering system design	4, 11
Serdy, James	35-011	serdy@mit.edu		Mechanical Engineering	LMP - Research Tech Staff			?
Shah, Julie	33-305	arnold@MIT.EDU		Aeronautics and Astronautics	CSAIL		interactive robots	13

Figure 2: Excerpt of color-coded list of manufacturing PIs at MIT

The list grew from 147 to 199 researchers and contains their name, email address, web links, unit affiliation at MIT as well as coding of their research by a technology area identification number. The list of 24 technology areas is shown in Appendix I. A color-coding scheme was developed to carefully keep track of who had been contacted, scheduled, interviewed and who was unavailable during the timeframe of this research. In total we conducted and documented 30 interviews at MIT between July 1, 2011 and September 1, 2012.

Figure 3 shows the distribution of manufacturing researchers at MIT (*N*=147) by their primary affiliation. There is manufacturing-related research happening across the campus and in total we were able to identify manufacturing PIs in 19 units at the Institute.

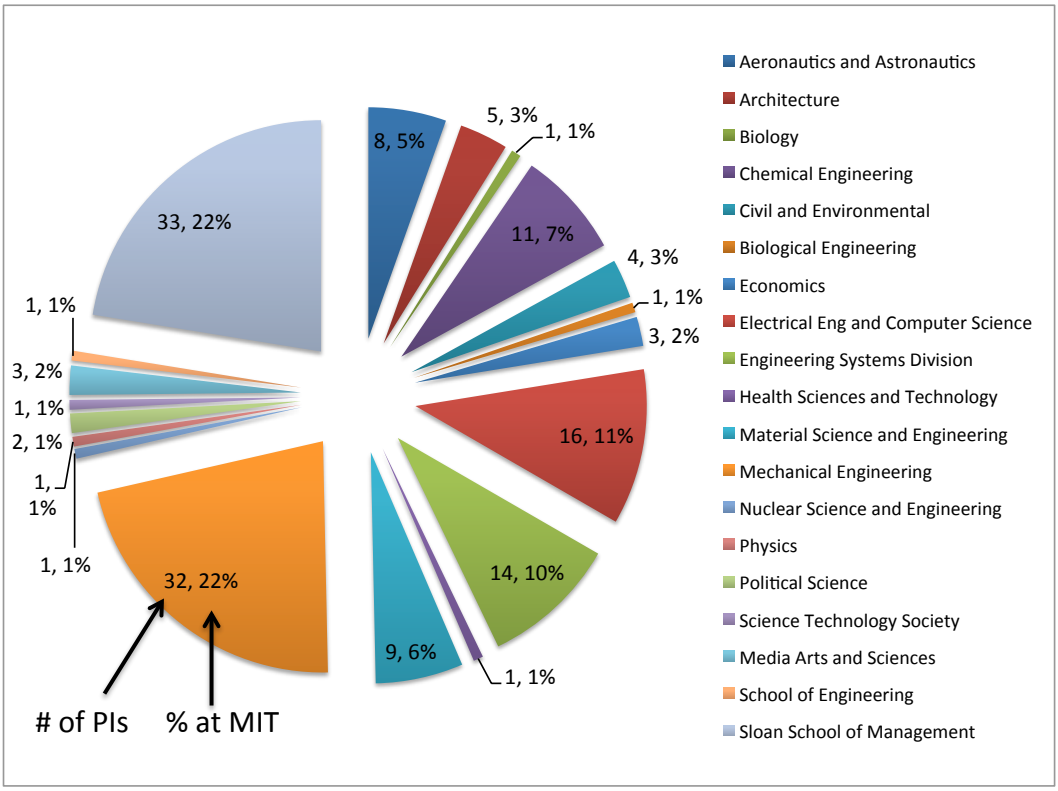


Figure 3: Distribution of manufacturing PIs at MIT by primary affiliation

We found that 72% of researchers with interests in manufacturing are affiliated with the following five academic units: Department of Mechanical Engineering (22%), Sloan School of Management (22%), Department of Electrical Engineering and Computer Science (11%), the Engineering Systems Division (10%) and the Department of Chemical Engineering (7%). In summary, we find that manufacturing research is active and very distributed at MIT. Aside from a number of crosscutting programs such as the Laboratory for Manufacturing and Productivity (LMP) and the Leaders for Global Operations (LGO) program there are no central coordination mechanisms. MIT is currently considering the creation of "mission-driven" research initiatives that could provide such coordination in the future.

At the outset of the research we hypothesized that it would be useful to group manufacturing-related technologies in some logical and consistent fashion, rather than providing a "laundry list" of technologies without much context or structure. The table in Appendix I shows a list of 24 manufacturing related technologies that we initially generated based on our own experience, the early findings of the MIT internal scan and the lists of technologies that had been proposed by a number of recent reports on manufacturing (see details below).

We subsequently grouped these technologies (before conducting the external survey) according to where they fit into the overall manufacturing process, see Figure 4.

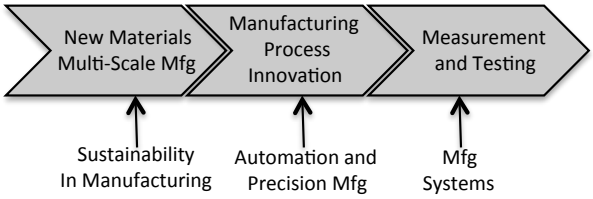


Figure 4: Manufacturing Technology Areas – initial grouping

This initial grouping is also shown in Appendix II. First, there are technologies such as rapid prototyping (e.g. 3D printing) and maskless lithography that are manufacturing process innovations. These are innovations that improve, enhance or replace existing manufacturing processes. Next, we identified technologies that produce new types of materials and enable multi-scale manufacturing and are subsequently fed into manufacturing processes. Third, we identified technologies that improve the way we perform measurement and testing during or after manufacturing.

Fourth, are technologies that increase the degree of automation and improve the precision of manufacturing through a combination of robotics and automation equipment and intelligent scheduling algorithms. These technologies primarily support the mainstream manufacturing processes shown in the center of Figure 4. The fifth area involves innovation in the manufacturing "systems" that surround the core manufacturing processes. These include supply chain management and logistics, information technology for manufacturing and manufacturing simulation and visualization. Finally we identified technologies that improve the environmental and economic sustainability of manufacturing through more efficient consumption of energy and increased use of recycled materials.

With the identification of MIT researchers and the coding of manufacturing technology areas completed, we set out to interview PIs and visit laboratories. In total we conducted 30 interviews and laboratory visits. Each interview was documented in a short written report. We also requested one or two key publications in each technology area.

Figure 5 shows a representative sample of about half the manufacturing research exemplars we found. We were able to see what new technologies are emerging in our labs that have the potential to greatly enhance or even transform manufacturing as we know it today. We briefly describe each area of technology research shown here and provide some key publications in the bibliography where appropriate. We proceed roughly from the upper left to the lower right.

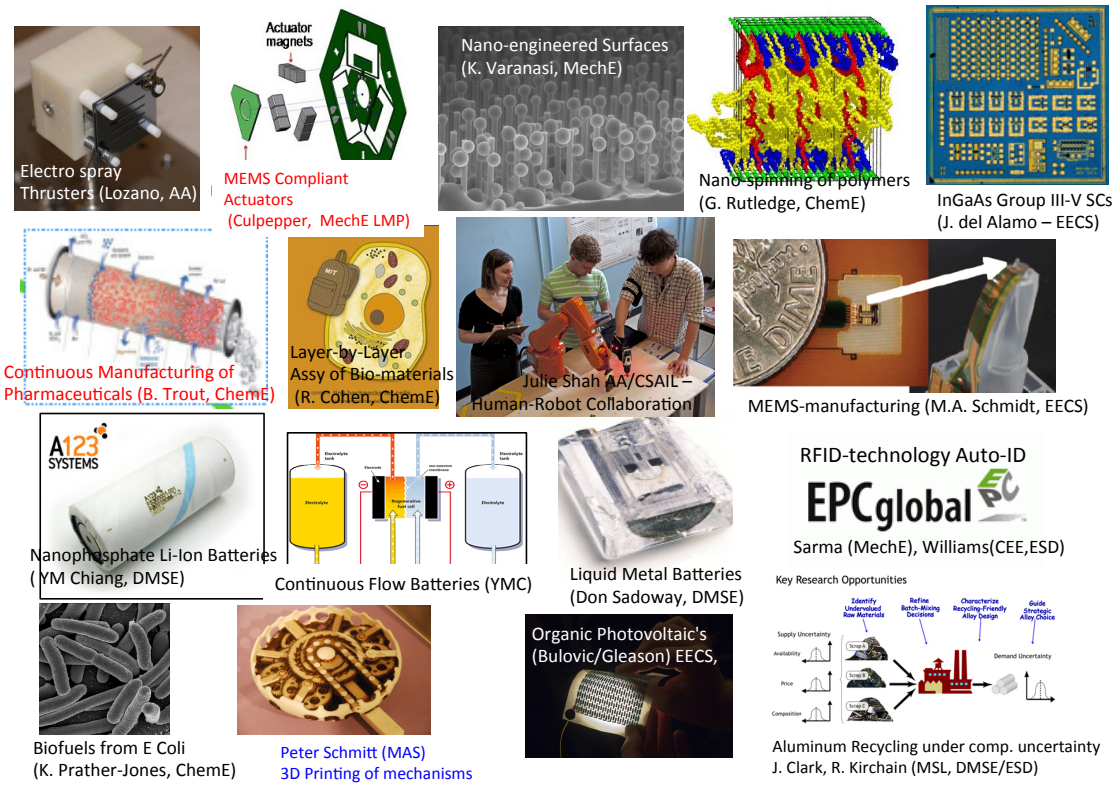


Figure 5: Sample of advanced manufacturing technology research at MIT

Prof. Paulo Lozano (Department of Aeronautics and Astronautics, technology ID 9) develops small thrusters using the concept of electro-spray propulsion [2]. This requires precision manufacturing of an array of needles from which ionized fluid droplets can be accelerated to great speeds using an electrical potential of about 1,000 Volts. This innovation has the potential to transform the manufacturing of small satellites and provides propulsive capabilities to very small satellites the size of a 10cm-cube therefore enabling a new industry segment to emerge.

Prof. Marty Culpepper (Department of Mechanical Engineering, technology ID 9) develops Micro-Electro-Mechanical-Systems (MEMS) such as very small compliant actuators [3] that have the ability to manipulate and position very small components such as gears and motors to in order to reliably assemble very small systems. Such nano-manipulators, built at US$ 2000 cost (excluding electronics) can be used for ultra-precision alignment of fiber optics and other small components during assembly of highly miniaturized systems.

Prof. Kripa Varanasi (Department of Mechanical Engineering, technology ID 15) has developed the capability to tailor the structure of surfaces in such a way that surfaces improve their properties such as their hydrophobicity (ability to reject water and other liquids) by significant amounts [4]. This could significantly improve the efficiencies of heat exchangers and other chemical process equipment and change the way that large-scale industrial components are manufactured.

Prof. Gregory Rutledge (Department of Chemical Engineering, technology ID 12, 14, 24) specializes in the electro-spinning of polymers [5], allowing assembling long molecular polymer chains into precise fibers and 3D structures. These materials can match and in many cases exceed the properties (e.g. tensile strength) of naturally occurring materials and therefore enable new products and applications in a wide variety of fields.

Prof. Jesus Del Alamo (Department of Electrical Engineering and Computer Science, technology ID 1,6,17) and his group are working on the next generation of non-Silicon semiconductors [6,7]. Specifically, he is investigating the potential of Gallium-Arsenide based semiconductors such as those based on InGaAs Group III-V materials. These have the potential for generating quantum-well field-effect transistors for ultra high speed, low power logic applications and extending "Moore's Law" down to nano-scale transistors and integrated circuits.

In the area of manufacturing of small molecule pharmaceuticals Prof. Bernard Trout (Department of Chemical Engineering, technology ID 5,10) and his colleagues are working on shrinking the size of chemical manufacturing plants by several orders of magnitude by enabling a continuous (non-batch) process for pharmaceutical manufacturing [8,9]. Firms like Novartis are very interested in this approach due to its potential for transforming the flexibility and economics of the industry. One of the pre-requisites for this approach is real-time in-situ sensing and control of chemical processes as well as continuous crystallization processes together with a variety of novel separations and final finishing processes.

Work by Prof. Robert Cohen (Department of Chemical Engineering, technology ID 5,24) and colleagues focuses on layer-by-layer (LbL) assembly of materials to produce substrate-conformal, ultra-thin structures with good dimensional precision and control over chemical functionality, optical properties and wetting characteristics. This work has been adapted recently to problems at the biotic/abiotic interface in the form of ultrathin, payload-bearing backpacks that are attached to living immune cells [10]. This research may enable the next generation of biologically enabled materials and production processes.

Prof. Julie Shah, a new faculty member in the Department of Aeronautics and Astronautics and CSAIL (technology ID: 13, 21, 22) is investigating techniques and algorithms for collaborative human-robotic work [11]. This research shifts the paradigm from robots replacing human labor to robots complementing human labor. This requires robots to become aware of human presence and intent and the development of robust multi-agent task allocation and scheduling algorithms under tight precedence constraints.

Prof. Marty Schmidt (Department of Electrical Engineering and Computer Science, technology ID: 1,6,17) is investigating new techniques for manufacturing low volumes of customized MEMS devices using equipment and processes originally designed for high volume semiconductor chip production [12]. With this approach one can manufacture micro-chemical reactors, pressure sensors, and a lot of other devices for sensing of small-scale physical, biological and chemical processes.

Much research at MIT is related to advances in the design and production of energy storage and energy conversion devices. Examples include nano-phosphate lithium ion [13] and continuous flow batteries (Prof. Yet Ming Chang, Department of Material Science and Engineering, technology ID: 8, 10, 24) and liquid metal batteries with potential application to grid storage [14] (Prof. Don Sadoway, Department of Material Science and Engineering, technology ID: 8, 16, 24). What this research has in common is the leveraging of advances in material science to increase the energy storage density, cost and charge-discharge characteristics of batteries. The main markets for energy storage are related to portable consumer electronics, the next generation of electric and hybrid vehicles as well as grid storage of electricity.

There is much exciting research in the ecosystem that enables and supports effective manufacturing including the tracking of goods inside and outside of factories in the broader supply chain. The work done by the Auto ID lab under Prof. Sanjay Sarma (Department of Mechanical Engineering, technology ID: 2,22) and his colleagues was essential in enabling the application of radio-frequency identification (RFID) technology to real-time sensing and tracking of end items in manufacturing value chains. An important contribution here was the definition of the Electronic Product Code (EPC) standard [15]. One of the critical applications of RFID technology is the rapid detection of duplicate serial numbers to prevent product imitations to enter the supply chain.

Prof. Kristala Jones Prather (Department of Chemical Engineering, technology ID: 5,20) designs modified E Coli bacteria to produce biofuels with tailored chemical properties [16]. This in essence turns cells and bacteria into small "programmable" biological factories. The challenges lie in ensuring consistency of biological processes and the ability to scale up processes to macroscopic quantities. While much of biological engineering and manufacturing is geared towards medical applications, recent interest in producing biofuels has risen sharply.

Three-dimensional printing and rapid prototyping of mechanical assemblies is the focus of Peter Schmitt's work at the Media Lab (technology ID: 3) [17]. One of the latest accomplishments is to print a functional watch movement in one single operation, rather than printing all parts individually, followed by manual assembly. MIT has been a significant contributor to precision prototyping machines over the years including in the area of waterjet cutting (OMAX Corporation) and 3D printing (e.g. Z-Corp).

Prof. Karen Gleason (Department of Chemical Engineering, technology ID: 1, 6, 15, 17) and her colleagues are working on so called organic photo-voltaics. This thin film technology enables solar cells that can be printed onto organic materials such as sheets of cellulose (e.g. paper) or fabrics as a substrate [18]. While the efficiencies demonstrated to date are still low (a few percent) there is the prospect that we may one day have electronic components woven into or printed onto our clothes and other flexible substrates.

One of the main tenets of the lean manufacturing movement is to increase productivity by reducing work-in-progress (WIP) and inventories of materials, parts and finished goods in the supply chain. However, as supply chains become leaner they also become more

vulnerable to supply chain interruptions caused by natural disasters, acts of terrorism or strikes. Much research is being carried out in improving our understanding of how resilience in supply chains can be achieved (Prof. Yossi Sheffi, Engineering Systems Division, technology ID: 2,22) through the use of better modeling, planning and visualization techniques and intelligent use of logistics clusters [19].

A part of the bigger story around sustainable manufacturing is the ability to recycle materials such as metal alloys with unknown or uncertain impurities as in the re-melting of multi-source aluminum. Dr. Randy Kirchain and his colleagues (Material Systems Laboratory, technology ID: 4, 12, 14) are working on techniques and algorithms for robust collection, alloying and pricing of aluminum and other recycling streams under compositional uncertainty [20].

The examples discussed here represent only a sample of what we are seeing at MIT in terms of manufacturing and production related research today. However, this sample together with the broader set of investigations (see Figures 2 and 3) brings up the following question:

How can the research in advanced manufacturing technologies be organized in a meaningful way?

While the innovations described above are all promising it is important to understand how they relate to each other and how they are infused in or change the way that manufacturing is done today.

Grouping of manufacturing technologies into 7 categories

There are several conclusions that come from our internal research scan at MIT. First, we found that there is "critical mass" in terms of faculty and researchers actively working on manufacturing-related topics. This research is distributed across the Institute and involves at least on the order of 150 faculty members (about 15% of the active faculty at MIT).

The research is generally motivated by real problems in industry but tends to tackle long term issues and out-of-the-box highly innovative concepts that may be game-changers and involve significant amounts of risk and upside opportunity. The research we see tends to be non-incremental and quite distinct from the type of research happening at more applied universities that tend to cater more directly to the needs of established firms. The majority of manufacturing funding at MIT comes from federal sources (such as NSF, DARPA, NIH etc…) and a significant portion of the research has the potential to generate new patents and startup firms (see chapter on scale-up).

There is currently much collaboration between pairs of faculty members or laboratories (e.g. those involving the Laboratory for Manufacturing and Productivity LMP) but these collaborations are not coordinated at a higher level at this time.

Based on reorganizing and clustering the responses from the internal scan we decided to group manufacturing technology research into the following seven categories. These categories are similar but more semantically consistent than the initial grouping shown in Figure 4. While some technologies could belong to more than one category we found this grouping to be more helpful than the flat list of 24 technology areas (see Appendix I).

The seven technology categories are as follows:

1) **Nano-engineering of Materials and Surfaces:** This involves the synthesis and structuring of functional and multi-functional materials at the nano-scale [10^{-9} m] and micro-scale [10^{-6} m] from the ground up. The materials include inorganic metals and composites but also increasingly biological materials and complex polymers. These technologies do not simply modify materials as they exist in nature, but create synthetic materials that may not have direct counterparts in the natural world.

2) **Additive and Precision Manufacturing:** This category of technologies includes new manufacturing processes that build up macroscopic parts layer-by-layer and achieve complex three-dimensional shapes starting from ingredients in powder or wire form. Often these processes are completely numerically controlled and avoid the need for expensive custom tooling. The creation of compliant actuators and sensors that can operate at small scale also fits into this group.

3) **Robotics and Adaptive Automation:** This group of technologies focuses on the intelligent use and adaptation of robots and automation equipment in manufacturing. These technologies either replace or augment human labor during manufacturing, particularly where very high precision is needed, where tasks are easily standardized and repeatable and where large forces and torques are required. New ways of programming and reconfiguring human-robotic teams and building in adaptability are also being actively pursued in this category.

4) **Next Generation Electronics:** It has been well documented since the 1960s that electronics manufacturing has progressed according to Moore's law [21], roughly doubling the number of transistors per processor every 18 months. However, semi-conductors based mainly on rigid silicon-based substrates may be reaching physical and economic limits by 2020 or so. The next generation electronics is currently under development including those using other materials such as GaAs-based semi-conductors, maskless lithography processes for "printing" circuits – avoiding the need for expensive masks - and the development of organic or flexible substrates.

5) **Continuous Manufacturing of Pharmaceuticals and Bio-Manufacturing:** Significant efforts are underway to scale down the chemical production of small molecule drugs while providing more flexibility and real-time monitoring and control. This may not only improve the efficiency of manufacturing for "blockbuster" mainstream drugs but also enable economic manufacturing of niche or so-called "orphan" pharmaceuticals. Parallel research is underway to turn cells and bacteria

into small programmable factories that have the ability to produce custom-designed proteins and compounds on demand. While both pharmaceutical manufacturing and bio-manufacturing are included in this group, their underlying challenges are quite different.

6) **Design and Management of Distributed Supply Chains:** The sixth category of research involves planning and managing large and distributed networks of suppliers in multi-echelon supply chains. This set of technologies consists of standards, information technology, algorithms and database management techniques for planning and tracking millions of individual items that are flowing through factories, distribution centers and retail stores. The role of the internet in creating real-time traceability with RFID, UID and other technologies is constantly growing. Besides the ability to efficiently handle the logistics of less-than-truckload shipments one of the functions of these technologies is to prevent fraudulent imitations from reaching the end consumer. One of the reasons for this category is the increased specialization of previously highly vertically integrated firms.

7) **Green Sustainable Manufacturing:** The scarcity and apparent monopolization of some materials such as rare Earth elements [22], the increases in transportation costs as well as new environmental regulations and customer perception promote more sustainability in manufacturing. These efforts center primarily on closing material loop cycles through reuse, remanufacturing and recycling of materials as well as the minimization of energy consumption during manufacturing.

External Survey of U.S. Academic Programs in Manufacturing

An external survey was administered as part of this research to solicit the views of 85 leading programs in manufacturing and industrial engineering in the United States. The list of programs was obtained from the ranking of leading programs listed in U.S. News and World Report from PhD granting institutions [23]. In total we achieved a response rate of 34% (N=29 responses). The geographical distribution covers the major regions of the U.S. where manufacturing takes place and leading universities in manufacturing are active.

The first question on the survey was open-ended and was intended to solicit manufacturing technologies and research areas that are being seen as particularly promising. The open-ended question was deliberately asked first in order not to bias respondents by providing a list of technologies that might constrain their answers.

Which technologies or innovations have the potential to lead to significant new manufacturing and production in the future? List three to five promising ones and explain.

The responses that were obtained are listed below. After some regrouping and organizing it was found that the seven manufacturing technology categories found in the MIT internal survey (see above) were also applicable to the external survey responses.

A summary of responses is provided here:

Nano-Engineering of Materials and Surfaces
Large area graphene production
Roll-to-roll manufacturing
3D integrated circuits for semiconductors
Nano-engineered fiber-composite materials
Nano-etching of surfaces

Additive and Precision Manufacturing
3D-Printing at Home (an extension of current inkjet printers to physical objects)
Rapid prototyping directly integrated into computer-aided design (CAD)
Next-Generation Injection Molding
Advanced Electrical Discharge Machining (EDM)
MOSIS-like foundries (http://www.mosis.com) for prototyping of physical parts
Laser-based manufacturing (fast control, short pulse)
Aluminum, Titanium, and Nickel based sintering and forming of custom parts

Robotics and Adaptive Automation
Intelligent smart automation
Embedded sensors in products and processes
Reconfigurable robotics
Human-robot collaboration
Wireless real time sensing
Networked control for tele-robotics and remote operations

Next Generation Electronics
Ultraviolet (UV) nanolithography
Multifunctional devices with integrated sensing and control
Computer interfaces (touch, voice, brain waves)
Wireless revolution in manufacturing (wireless factories)
Flexible substrates for electronics

Continuous Manufacturing of Pharmaceutical and Bio-manufacturing
Stem cell-based manufacturing
Human organ engineering and manufacturing
Regenerative and personalized medicine
Tissue manufacturing

Design and Management of Distributed Supply Chains
Community-based design
Open-source design of complex cyber-physical products and systems (e.g. AVM [24])
Decentralized supply chain management
Cloud computing for CAD/CAE/CAM

Green Sustainable Manufacturing

New energy sources: low cost high efficiency photo-voltaics (PV)
Concentrated solar power (CSP) for manufacturing
Impact of availability of U.S. natural gas on energy-intensive manufacturing
Waste-to-energy conversion
New battery storage technologies
Super-capacitors for energy storage
Waste power/energy capture within plants
Re-manufacturing and recycling at larger scale

While the responses to the external survey represented a mix of product and process innovations, they by-and-large validated our grouping of manufacturing technology manufacturing into seven categories. It was also interesting to see that responses clustered with geographical areas that are typically associated with leading expertise in certain manufacturing areas such as metal manufacturing in the Midwest, pharmaceuticals and bio-manufacturing in the Northeast and Southern California as well as electronics in Northern California (Silicon Valley). It also appears that newer areas of regional design and manufacturing expertise are emerging such as manufacturing research related to photo-voltaics and water-management systems in the Southwest of the U.S. (e.g. Arizona) where there is an abundance of sunshine and a scarcity of water.

The next question on the survey asked respondents to rate the list of 24 technology areas (see Appendix I) in terms of their promise over the next 5-10 years. The exact wording of the question is as follows:

Please rank the following manufacturing research areas in terms of promise or potential to achieve large advances in manufacturing in the next 5-10 years

The responses were recorded on a scale from 1 to 5 with 1 being the least promising and 5 being the most promising.

Figure 6 shows a statistical analysis of the 24 technology areas in decreasing order of average promise on the 1-5 scale from left to right. The horizontal thick bar shows the average score achieved by a technology area. It is noteworthy that on average all technologies were ranked as at least a 3 on the 5-point scale. The vertical bars show the +/- one standard deviation (1σ) assessment from the mean.

The six technologies that achieved an average rating of greater than 4.4 are shown in the box on the left side of Figure 6. These are technologies that received the highest rating and have a relative small standard deviation ($\sigma<1.0$). To the right we find three technologies that exhibited the highest variances in respondent evaluations ($\sigma>1.0$):

- Supply chain and logistics
- Rapid prototyping
- Flexible electronics

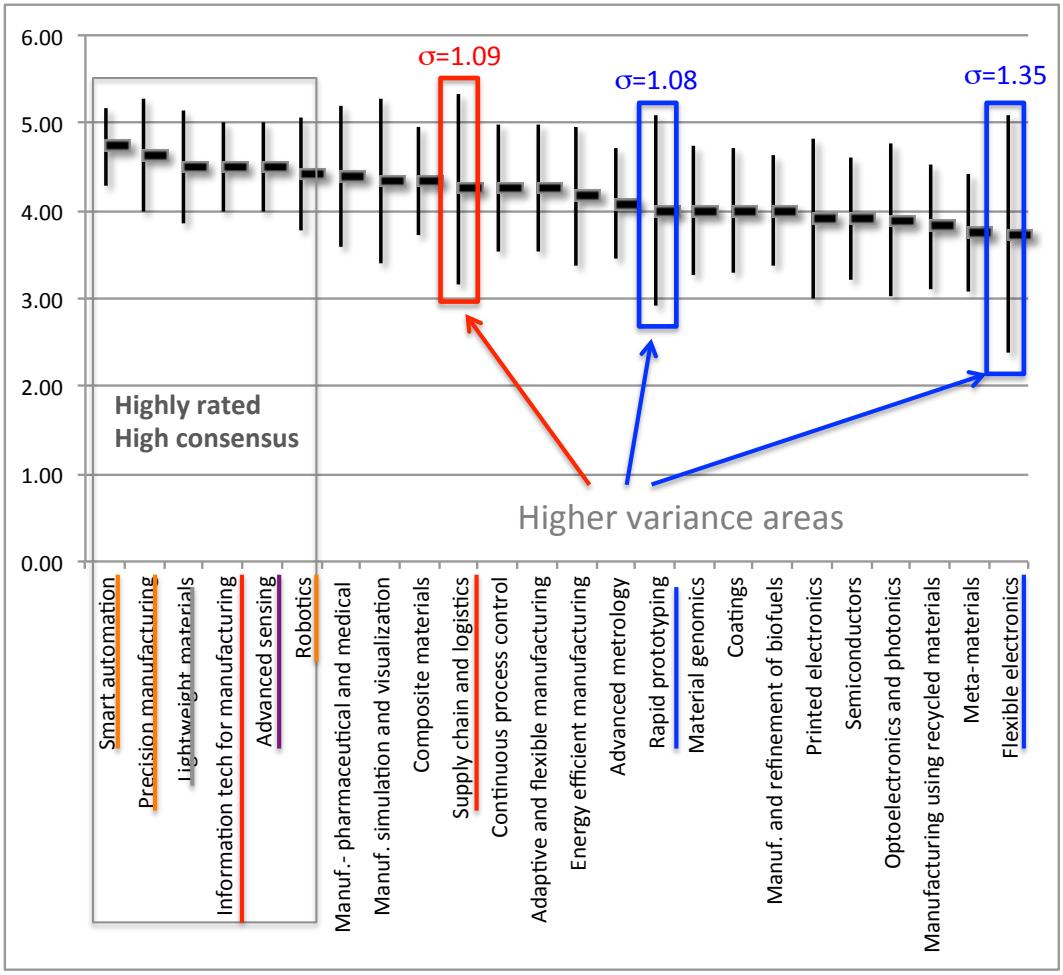


Figure 6: Quantitative rating of 24 technology research areas

Two interesting observations follow from this data:

1. The top group of six technologies with high ratings (>4.4) contains all three technology areas that were listed in the automation and precision manufacturing group (see Appendix II). These technologies all aim at increasing efficiency and decreasing the direct manual labor content of manufacturing. New kinds of robotics and automation, some acting as assistants to humans, fall into this category. Other areas that were highly rated are the development of lightweight materials (e.g. advanced composites) and an increase in the number of advanced sensors and associated information processing during manufacturing.

2. The second observation is that some technologies exhibited high variances in terms of how respondents rated them. Some technologies do not reflect consensus but some amount of disagreement in terms of their future potential. Three technology areas with a standard deviation greater than 1.0 (on the 5-point scale) emerged: Technologies serving to improve supply chain management and logistics, rapid prototyping and flexible electronics. The controversy surrounding rapid prototyping

is often under-appreciated. While proponents of the technology claim that we will soon be able to manufacture many (or even most) products directly with rapid prototyping machines, perhaps even from our homes, detractors point out that parts manufactured through such techniques often to not have the necessary lifetime properties (such as hardness, durability, fatigue life...) that are required to support heavy duty real world use. Likewise, opinions differ about the prospects of electronic circuits printed onto flexible substrates.

Another question on the survey elicited challenges faced by U.S. academics in the area of manufacturing technology research. The exact wording of the question was as follows:

In your department and your university, what are the institutional challenges of encouraging research in those areas which you have identified above as most promising? Are faculty incentivized to work in these areas? How are students recruited into them? How are these efforts funded?

A summary of responses is provided below. In essence the challenges facing U.S. university-based researchers in manufacturing fall into two broad areas: Resources Limitations and Collaborations with Industry:

Limited Resources

It was reported that the financial resources needed to create and maintain sophisticated infrastructures for manufacturing research at a university are often too large. As a consequence such research does not happen, or universities partner with local or regional industry to carry out research (see more below).

The level of vigor in manufacturing research is mainly driven by federal funding priorities (e.g. NSF, DOD, DARPA…). When the federal government makes manufacturing research a priority and provides funding, then universities apply for grants and pursue such research. An example is the recent DARPA "Adaptive Vehicle Make" program [24]. On the other hand, when federal priorities shift and the funding goes away, so does the ability of many universities to work in these areas.

There is fierce competition for faculty slots by other areas. Manufacturing is often not perceived as a "hot" or promising leading edge area of research by university senior administrators and faculty search committees. Faculty members often "disguise" or "dress up" their research interests in manufacturing by highlighting the connections of the research to the underlying fundamental physics or biology rather than the real world applications of their work.

At many universities only a sub-critical mass of faculty and students are interested in manufacturing. Many tend to gravitate more towards other areas perceived as more attractive, e.g. energy, robotics, but that may have indirect relevance to manufacturing.

Several respondents highlighted that it is difficult (but not impossible) to get U.S. born students interested in manufacturing research and careers.

Collaborations with Industry

Universities will use industry facilities to build prototypes and test research ideas, but often give intellectual property (IP) rights mainly to the industry sponsor. It appears that a substantial number of universities are willing to trade away some, or all, of their IP rights from inventions arising out of the research in exchange for access to sophisticated facilities.

Industry wants quick answers, while faculty and students want to publish and do longer term projects (mismatch in expectations, timescales). There appears to be a tension between the incentives and interests of most faculty members and the need for companies to solve problems that arise in their day-to-day manufacturing operations.

Many firms no longer keep strong R&D departments and centers in house.

Academic researchers are generally interested in working on problems motivated by industry but often feel "shackled" by industry legal staff when trying to reach agreement on sponsored research.

Several academic respondents articulated a need to develop joint value propositions (cost/benefit) for manufacturing technology research in the U.S.

As part of the survey, some respondents made suggestions for improvement. These mainly center on creating institutional arrangements and incentive structures that provide long term stability around manufacturing technology research. Two examples of comments that we found illuminating are quoted below:

"*Manufacturing is broad, which involves materials, processes, systems, sustainability, and many more. Experts in those areas are affiliated with different departments and colleges. So, an institutional challenge is a mechanism to identify experts from different units and promote collaboration among them. Our university has identified three strategic research areas, which include 1) Bioresearch, 2) Optical Sciences and Technology, and 3) Water and Environmental Sustainability. And, our university supports creative research efforts in these areas via a special investment available from a state tax fund. Recently, our college (college of engineering) also created a mechanism to promote collaboration among multiple PIs in these areas by providing a seed fund on a competitive basis. […] The above mentioned investment fund from the state tax not only supports research activities, but also provides significant supports for recruiting students (e.g. fellowship, scholarship, travel support of students for conferences)*."

"*One of the major challenges would be a sustainable funding mechanism for long-term collaboration (as opposed to projects that need to be renewed year by year). In fact, our faculty members have been teaming up with industry partners to seek a large-scale, multi-*

year project from various agencies (e.g. DARPA), and this could be a mechanism to overcome the above mentioned challenges."

Taken together these comments suggest that there is room for new mechanisms and organizations that bridge between industry and academia in U.S. manufacturing research. Such institutions could be modeled after the German Fraunhofer Institutes that have been very successful in bridging between university and applied industry manufacturing research [25]. The non-profit Manufacturing Innovation Institutes (MIIs) that have recently been proposed by the American Manufacturing Partnership (AMP) [26].

Cross-Comparison of Technology Areas in Manufacturing Reports

A number of important reports that have been published on manufacturing in recent years stressed the importance of innovation and the role of manufacturing technology research. However, we have found that many of the technology lists that are provided as part of these reports are either very high-level and generic or contain partially overlapping lists of technologies. In Table 1 we map the manufacturing-relevant technologies from the following five reports to the seven manufacturing technology categories discussed earlier:

1- PCAST Report on Ensuring American Leadership in Advanced Manufacturing – June 2011 [27]

2- AMP Report on Capturing Domestic Competitive Advantage in Advanced Manufacturing – July 2012 [26]

3- IDA Report on Emerging Global Trends in Advanced Manufacturing – March 2012 [28]

4- U.S. Manufacturing Competitiveness Initiative – Make: An American Manufacturing Moment – December 2011 [29]

5- McKinsey Global Institute, McKinsey Operations Practice, Manufacturing the future: The next era of global growth and innovation, November 2012

The rows of Table 1 show the (color-coded) seven technology categories and the columns correspond to five reports published between June 2011 and November 2012. We find much agreement amongst the findings of these reports and our own research. Additive and precision manufacturing is mentioned in three out of five reports. The importance of nano-engineering and new materials is discussed in all five reports. Consistently mentioned are lightweight materials (e.g. low cost carbon fiber composites) for application in fuel-efficient vehicles and the development of biocompatible materials for medical devices. Next generation electronics are discussed in three out of five reports, particularly with respect to optoelectronics and photonics. Advances in robotics and automation are featured in four out of five reports, particularly in the context of enabling higher degrees of flexibility. Green and sustainable manufacturing is mentioned in four reports, focusing mainly on closing materials cycles and waste recovery.

Bio-manufacturing appears in every report and is perhaps viewed as one of the most innovative areas where U.S. research is world leading and promising. Finally, the broad category of design methodology and supply chain management is also universally mentioned. However, different reports emphasize different aspects of this category.

Table 1: Cross-comparison of advanced technology research areas in recent reports

Topic	1 - PCAST	2- AMP Report	3- IDA Report	4 - US Manufacturing Competitiveness Initiative	5- McKinsey Global Instutute Report
Additive and Precision Manufacturing		Additive manufacturing Advanced forming and joining technologies	additive manufacturing		Additive Manufacturing
Nano-Materials and Surfaces	Nano-scale carbon materials materials by design Nanotechnology enabled medical diagnostic devices and therapeutics	Advanced materials design, sythesis, and processing Nanomanufacturing	advanced materials	materials science advanced materials	Nanomaterials Lightweight materials
Next Generation Electronics	Flexible electronics nanoelectronics Next generation optoelectronics	Flexible electronics manufacturing	semiconductors		
Robotics, Smart Automation, and Adaptability	advanced robots flexible manufacturing facilities	Industrial robots Advanced sensing, measurement, and process control	move towards rapid changability in manf		Advances in industrial robotics
Green/Sustainable Manufacturing		Sustainable manufacturing	support for sustainable manf	smart manufacturing	Green Manufacturing Cicular economy
Pharmaceutical Manufacturing Biomanufacturing	biomanufacturing	Biomanufacturing and bioinformatics.	biomanufacturing	biotech biomimicry	Biotechnology and Biological Agents
Supply Chain Design and Management	design tools that improve the systems engineering, integration, and testing process open source collaboration environments for the design process	Visualization, Informatics, and Digital Manufacturing Technologies Advanced manufacturing and testing equipment	increased reliance on information technology modeling and simulation in manuf process acceleration of innovation in supply-chain management	next generation supply networks and advanced logistics high performance computing	Innovation in product design; Frugal innovation Digital modeling, simulation and visualization Business Models: Mass Customization

Literature Search on Advanced Manufacturing Technology Research

Using the ISI Web of Science we conducted a literature search of papers written on advanced manufacturing research between 2008 and 2011. A large fraction of the published manufacturing research conducted in the U.S. is concentrated in about a dozen universities, which include the six universities that are represented in American Manufacturing Partnership (AMP):

- Massachusetts Institute of Technology
- Carnegie Mellon University
- University of California Berkeley
- University of Michigan
- Georgia Institute of Technology
- Stanford University

Another set of universities is also active in applied research but tends to be less active in publishing their findings openly. We hypothesize that these universities are the ones that are more tied by IP arrangements with industry as discussed earlier. We found that published research in advanced manufacturing falls mainly into the following topics:

Smart Automation and Autonomy, Reconfigurable Manufacturing Systems, Process modeling, monitoring, and optimization, Machine Tools and Instrumentation, Design Integration, Rapid Prototyping and Additive Manufacturing, Micromachining, Sustainable Manufacturing, Bio-manufacturing, and Medical devices.

These topics map well into the seven technology categories. In total we were able to identify *558* peer-reviewed journal articles on advanced manufacturing during the aforementioned three-year period. We suspect that this is only a subset of the research published since many papers on manufacturing research are presented at conferences that are not listed on the Web of Science. In summary, we find that the U.S. continues to generate a steady stream of quality research on advanced manufacturing technology topics.

How Firms innovate and adopt Advanced Manufacturing Technologies

Innovation and advances in manufacturing research occur not only in academia, but also in established firms and in younger startup companies. This research tends to be driven by the needs of product development and the launch of new products (and associated services). Not all innovations end up as patents or publications and we find that many of them are kept as trade secrets and are carefully managed as company internal IP.

It is difficult to find data on company-internal R&D in advanced manufacturing. However, one of the best sources to understand the role of advanced manufacturing technologies and innovation in manufacturing are the ~200 company interviews we conducted as part of the

PIE project. The following list is a sample of what firms told us about the role of manufacturing technology innovation in their enterprises:

Cisco
Cisco is a manufacturer of networking equipment itself, but also provides services to manufacturers who wish to have better real-time visibility into the status of their plants. It was mentioned that remote networking, sensing and tele-operation of manufacturing plants enables real-time visibility and separation of command and control from physical operations in global manufacturing operations.
Technology categories: Smart Automation, Supply Chain Design and Management

Alnylam
Alnylam is an entrepreneurial firm focusing on RNAi (interference) technology that will enable suppression of a range of diseases "at the source" rather than suppressing symptoms, e.g. RSV, liver cancer, hypercholesterolemia. While mastering RNAi itself is very complex, the resulting drugs will be manufactured based on chemical pharmaceutical manufacturing rather than biologics. Many of the advances in small volume flexible manufacturing of pharmaceuticals will benefit firms like Alnylam.
Technology categories: Pharmaceutical Manufacturing

Michelin
Michelin is one of the largest and most successful tire manufacturers in the world with headquarters in France and a substantial footprint in the U.S. (especially in South Carolina). They operate centralized R&D facilities for products that have global applications and don't differ much by region, e.g. large Earth-moving tires. These products require innovative materials (e.g. combined rubber/steel composites) and advanced chemical and material handling processes. Michelin sees itself as leading its industry through innovation rather than cost reductions.
Technology categories: Nano-materials and Surfaces, Green Sustainable Manufacturing

Cambrian Innovation
Cambrian Innovation is a young startup firm focusing on the development of bioelectrical systems for environmental applications such as wastewater remediation and electricity production from biological waste. The ability to produce electricity from wastewater and produce value-added products like oxygen and methane relies mainly on electrically active biofilm technology that requires tight integration of the biology and electro-chemical process controls.
Technology categories: Biomanufacturing

1366 Technologies
This startup firm aims at increasing yields during photovoltaic (solar cell) production by direct "float glass" production of silicon wavers from molten baths, thus avoiding costly and inefficient shaving and grinding of ingots. This maps the technology to the additive manufacturing category and also is in line with the observed trend of turning batch process into continuous processes.
Technology categories: Additive and Precision Manufacturing

While a detailed survey of firms on trends in manufacturing technology innovation was beyond the scope of this effort we see that based on these examples and sets of interviews we conducted that the key trends observed in academic research also hold true for many manufacturing firms.

Definition of and Implications for Advanced Manufacturing

Now that the important trends and categories in advanced manufacturing research have been established, the question is: *So What? How do these manufacturing innovations impact and change manufacturing today and in the future?* In order to understand this better we need to map these technology categories to the generic architecture of a manufacturing enterprise. The diagram depicted in Figure 7 shows the layout of a typical manufacturing plant. We show this to illustrate the traditional view of what manufacturing is and what its various inputs and outputs are.

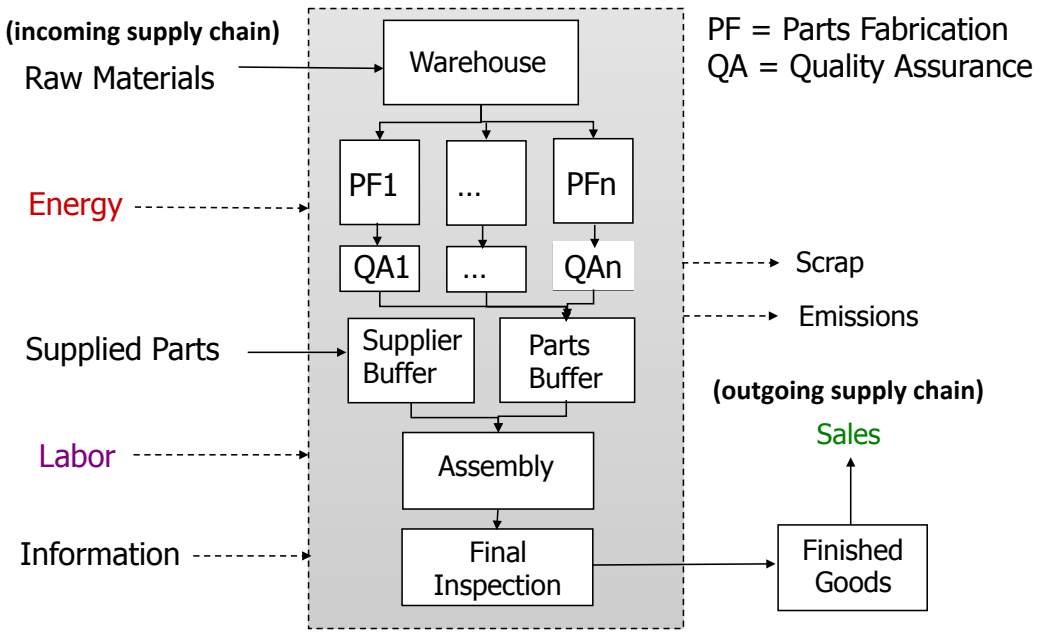


Figure 7: Layout of a traditional manufacturing plant

Traditional manufacturing is essentially the step-wise transformation of raw materials (coming from mainly natural sources such as underground mines, forests and so forth) into finished goods. Raw materials are provided to the manufacturing plant by the incoming supply chain and are temporarily stored in a warehouse. The function of the warehouse is mainly to serve as a buffer and to ensure that the production line will never be starved of upstream input materials. The next step is typically parts fabrication, i.e. the manufacturing of individual components that are the fundamental building blocks of the finished products. In a highly vertically integrated firm most of the parts are fabricated in-house (think Ford Model-T assembly line in the 1920s or Boeing aircraft in the 1970s and 80s). More recently

firms have become less vertically integrated and have increased the number of supplied or purchased parts that are coming in at some intermediate station and are then stored in an internal supplied parts buffer. Quality assurance (QA) is critical to ensure that both parts made in-house and those purchased from suppliers meet all the tolerances and other characteristics required by downstream manufacturing steps. Allowing defective parts to slip through to the next process step can be very costly and increases scrap and rework, while decreasing productivity. One of the recent trends in manufacturing has been to measure quality during the fabrication of parts (e.g. using statistical process control SPC) rather than after fabrication is complete. This allows catching problems much earlier, but requires sophisticated sensors and software and a higher level of integration and skill in the manufacturing plant.

Once parts are available, they are used for final assembly of the product. Depending on the complexity of the product, assembly may occur in multiple stages involving sub-assemblies, which can be put together on parallel pre-assembly lines that feed into the main production line. Once final assembly is complete a final inspection typically occurs, checking that the product works as intended and that it meets all requirements. Finished goods are subsequently stored for distribution to their intended markets through the outgoing supply chain.

Besides raw materials, there are several other key inputs into the manufacturing plant. These include supplied parts as already discussed, energy, typically in the form of fossil fuels or electricity, information from suppliers and machine vendors and customers as well as human labor of varying levels of skill. In order to increase productivity the amount and cost of these inputs per unit of output must be minimized. On the output side there is a need to maximize the useful outputs (finished goods) while minimizing non-value-added outputs such as scarp and emissions (air pollutants, residual chemicals...).

In the age of mass production (ca. 1910-1990) the emphasis was almost entirely on maximizing throughput and productivity of a manufacturing plant for a relatively small assortment of standard product configurations. However, since the late 1980s firms have become more aware of varying customer needs in different market segments. This has led to a larger number of variants on the production line and the challenges associated with manufacturing a larger variety of products, while maintaining high levels of quality and efficiency [31].

Another trend is that manufacturing is increasingly using the concept of a “push-pull” boundary. Whereas traditionally manufacturing plants would mainly schedule their output based on sales forecasts (“push”), many plants today only fabricate parts based on forecasts, but carry out assembly based on actual orders received (“pull”) on a per SKU (shop-keeping-unit) basis [32]. The Dell computer company was one of the early pioneers in this area also known as “postponement”. This requires a sophisticated integration of production planning and scheduling with plant operations and supply chain management. Higher levels of skill and flexibility are required from production facilities, staff and supporting information systems to deal with this dynamic complexity.

The insights we have gained in our research on advanced manufacturing technologies lead us to a much broader definition of what advanced manufacturing is in the 21st century. Traditional manufacturing is shown below (top of Figure 8) and consists mainly of fabrication and assembly and the making of finished goods in a more or less linear step-wise fashion. This is an abstracted and simplified view of what is shown in Figure 7.

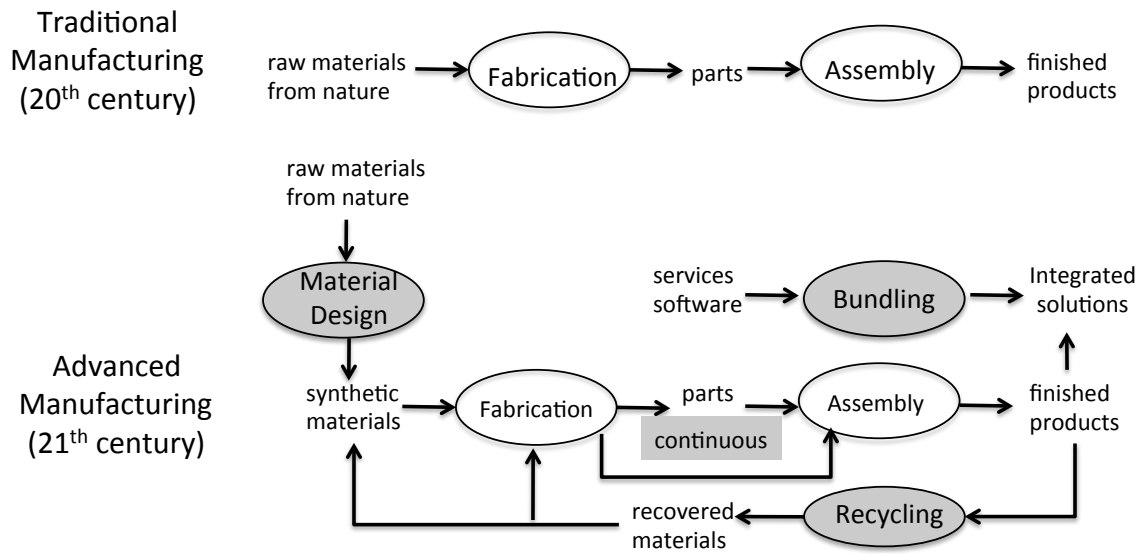


Figure 8: Definition of advanced manufacturing (bottom) as an expansion of traditional manufacturing (top)

We find through our internal and external surveys and firm interviews that this traditional linear view of manufacturing is no longer adequate. Manufacturing and production have become much broader and less linear and are changing in four fundamental ways.

First, Figure 8 (bottom left) shows that while fabrication and assembly are still essential and also form the core of manufacturing in the 21st century, that our ability to synthesize new materials is now so advanced that it must be considered as important a step as fabrication and assembly itself. We have always processed natural materials through a combination of mechanical, chemical and thermodynamic processes (e.g. by alloying) but the starting point was materials as they occur naturally. Material Design and synthesis allows creating materials from scratch and giving them internal and surface properties that are tailored and that do not occur naturally. This has profound downstream implications, e.g. the elimination of subsequent fabrication and assembly steps such as coatings that become unnecessary.

Second, we observe a blurring of the boundary between fabrication and assembly in addition to the introduction of ultra-efficient processes and automation. Traditional manufacturing was very batch-oriented and discretized the production process into a set of distinct steps, separated in time and space. Today, continuous manufacturing in batch sizes of "one" is increasingly practiced. This allows for more synchronous monitoring, eliminates intermediate buffers and increases process flexibility but also requires more sophisticated equipment, synchronization and in-depth knowledge.

Third, the "product" is often not just a physical artifact or widget but an integrated solution that involves bundling of physical products with services and software. A number of firms highlighted how the manufacturing of a physical product is often only a means to an end, i.e. the offering of an end-to-end solution to their customers. It was mentioned (e.g. by Cotter Brothers a manufacturer of process modules for the pharmaceutical industry) that the service portion of the product-software-service bundle often contributes the majority of profits. However, the service could often not be offered on its own, without deep know-how of the physical product. This is relevant for production since products that are part of a product-software-service bundle often contain more sensors, require higher quality and reliability and have more software content compared to traditional "inert" products.

Finally, the 4th trend is the return of recycled materials back to fabrication or even material synthesis. Here we can distinguish between reuse, remanufacturing and recycling depending on how far upstream the material cycle reaches. Increasingly, raw material prices have become more volatile [30] and supply controlled by few nations (e.g. Rare Earth Elements), thus there is a strong incentive for material recovery that goes beyond purely ecological and environmental considerations. The picture that 21st century advanced manufacturing presents is greatly expanded and more complex.

Based on this framework we propose the following definition of what is Advanced Manufacturing:

Advanced Manufacturing is the creation of integrated solutions that require the production of physical artifacts <u>coupled</u> with valued-added services and software, while exploiting custom-designed and recycled materials and using ultra-efficient processes.

The diagram in Figure 9 maps the seven manufacturing technology categories to this expanded view of manufacturing.

First, we see that research in nano-engineering of materials and surfaces directly enables "Material Design". We believe that this is not a mere enhancement of what was done previously but a fundamental new step in production that is as important as parts fabrication and assembly. Material synthesis has the potential to embed functionality directly in materials from the start (e.g. embedded sensors, functionally graded materials etc….) and may reduce the part count of products, while leading to more integral and lighter weight products in the near term future.

Advances in additive and precision manufacturing mainly benefit parts fabrication. Rather than starting with large chunks of material and removing what is not needed, additive precision manufacturing creates parts from the ground-up, for example by printing parts layer-by-layer. Another important objective is to reduce the need for customized and capital intensive tooling for parts fabrication.

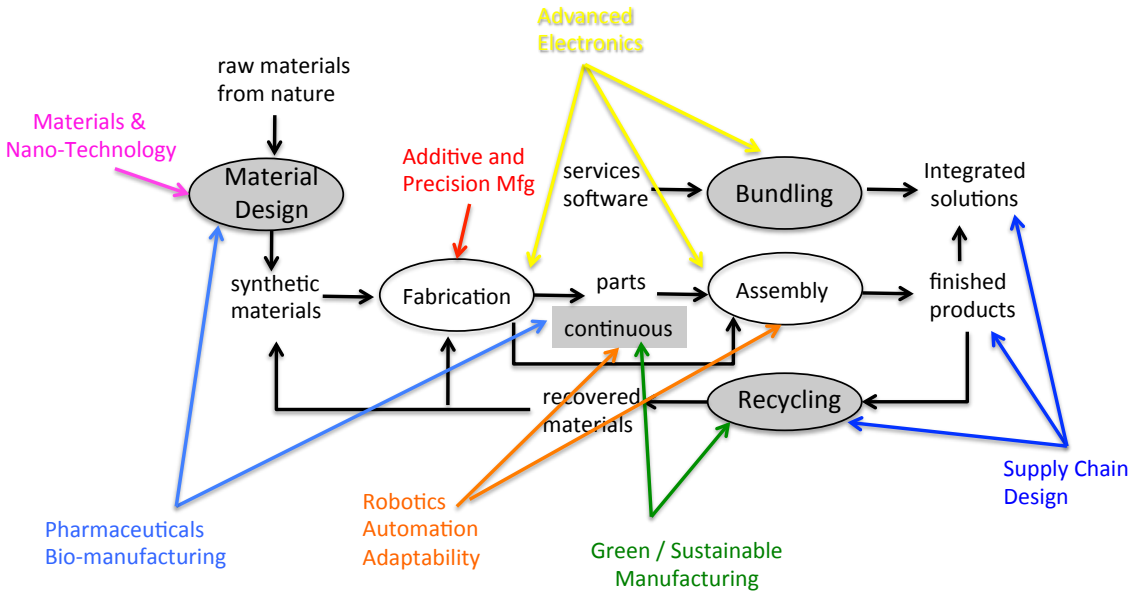


Figure 9: Impact of manufacturing technology research on advanced manufacturing

The technologies in the category of robotics, automation and adaptability aim to replace or augment human labor. Besides providing robots and automation equipment that is easy to program and maintain, while being flexible and reliable, there is a desire to reduce capital expenditures. With manufacturing wages in many countries in the range between $2 and $20 per hour, robots are becoming increasingly competitive when their acquisition and operation costs are considered relative to unit output produced. As fewer jobs are required for direct manufacturing labor due to automation, more people need to be educated and trained as operators, programmers and maintainers of automation equipment (see chapter on skills and education). Traditionally, robots have been used mainly during assembly but they are increasingly deployed upstream in fabrication as well as downstream in the supply chain (e.g. see Kiva Systems).

The category of advanced electronics impacts both the manufacturing process itself through improved sensing and control, but also through embedding sensors and electronics in products directly. In some cases embedded electronics are a pre-condition for bundling of physical products with services and software (e.g. GPS chips as a pre-requisite for location-based services). For example, products that can sense their own state and alert operators when certain maintenance actions are required offer opportunities for value added services. The role of the Internet in connecting the physical world with the virtual world is a significant aspect in this category.

Innovations in manufacturing of Pharmaceuticals and Bio-manufacturing begin with a deep understanding of function and structure at the molecular and cellular stage (Material

Design) and extend into the continuous processing of materials into more complex molecules and compounds such as new drugs and biofuels, among others.

Improvements in Supply Chain Design and Management impact especially the end of the value chain including the on-demand distribution of finished products, the management of information and data interfaces with customers as part of integrated solutions that bundle physical artifacts with software and services as well as the tracking and recycling of materials at the end of life. Besides tracking the flow of items through barcodes and RFID chips, innovations in supply chain management also impact the predictive scheduling of production and optimization of the "push-pull" boundary [32] (see also discussion above).

Finally, Green and Sustainable Manufacturing technologies help recover materials from waste streams and reduce significantly the environmental footprint and energy consumption of manufacturing. Even accurately determining the ecological footprint and the use of resources in manufacturing has given rise to innovative solutions and technologies.

Which of these technologies are developed and adopted by firms depends on the industry and location as well as strategic decisions by firms to seek competitive advantage. Our interviews suggest that innovation in some or all of the categories shown in Figure 9 is critical to many firms and that patterns of adoption do exist. Firms should carefully think about which manufacturing technologies they can acquire as commodities, and which ones are sources of competitive advantage to them.

Conclusions and Summary

We have observed significant amounts of innovation in advanced manufacturing technologies. MIT and other U.S. universities continue to innovate in some key technology areas related to manufacturing. Many of these innovations are potentially transformative, and not simply evolutionary. Evolutionary work is happening mainly at applied universities. Research tends to cluster into seven manufacturing categories that are somewhat orthogonal / complementary to each other:

Nano-engineering of Materials and Surfaces
Synthesis of multi-functional materials at the nano-scale from the ground up

Additive Precision Manufacturing
Building up components by adding layers of material in complex 3D shapes

Robotics, Automation and Adaptability
Using robotics to substitute for or complement human labor in new ways

Next Generation Electronics
Next generation circuits using non-Si materials, using mask-less processes and flexible substrates

Bio-manufacturing / Pharmaceuticals
Continuous manufacturing of small molecules, turning cells/ organisms into programmable factories

Distributed Supply Chains / Design
Enabling flexible and resilient decentralized supply chains, new approaches to web-enabled mfg

Green Sustainable Manufacturing
New manufacturing processes that use minimal energy, recycle materials and minimize waste and emissions

Firms also innovate and "pull" key technologies that open new markets or give specific competitive advantage. We define advanced manufacturing as being broader than traditional "linear" manufacturing: **Advanced Manufacturing is the creation of integrated solutions that require the production of physical artifacts <u>coupled</u> with valued-added services and software, while exploiting custom-designed and recycled materials and using ultra-efficient processes.**

Our external survey confirmed the need to find new models to enhance U.S. manufacturing research collaborations within universities, between universities and industry, and the strategic deployment of state and federal research dollars for maximum effect.

While the focus of this book is on the state and future of *U.S. manufacturing*, there is a need to take a global perspective and synthesize where we see the impact of new manufacturing technologies and capabilities. In the following we observe three main opportunities:

1. Technologies that are truly enablers of classes of products that do not yet currently exist. Examples of these include non-Si based semi-conductors, wearable electronics, new drugs and fuels from biology, and new micro-satellites with propulsive capabilities. Many of these have the potential to create – if not entirely new industries – new niches that may generate substantial demand and economic activity. *A key question is whether these new products will generate sufficient value and interest over time to co-exist with or partially substitute for existing products.*

2. "Programmable" manufacturing processes that do not rely on capital-intensive tooling and fixtures. One of the big trends we observe is to counteract the need for highly expensive and unique manufacturing equipment (e.g. $5 billion semi-conductor fabs). There are several critical questions that arise about these new flexible manufacturing processes: *Can they guarantee the required tolerances? Will they catalyze distributed manufacturing?* Examples of such technologies include 3D-printing, maskless nano-lithography and others discussed in this chapter.

3. Technologies that enhance productivity and flexibility in existing large scale manufacturing processes. These are technologies that are not so much game-changers as they are enhancing existing manufacturing and inserting themselves at key points along the value chain. *Will there be uptake in the U.S. industrial base?* Examples of such technologies include RFID tracking of parts during manufacturing and distribution, recycling of aluminum under compositional uncertainty, human-robotic collaboration and flexible automation.

Finally, we note that none of these trends may lead to a lot of new jobs. However, they will help preserve and transform existing jobs and the new jobs they do create will be meaningful, and require higher levels of skill and knowledge.

References

[1] Dertouzos, Michael L., Lester, Richard K., Solow, Robert M., and the MIT Commission on Industrial Productivity, "*Made in America: Regaining the Productive Edge*", MIT Press, ISBN 0-262-04100-6, 1989

[2] Lozano, P. , Martinez-Sanchez, M., Lopez-Urdiales J.M., "Electrospray emission from nonwetting flat dielectric surfaces", *Journal of Colloid and Interface Science,* Volume 276, Issue 2, 15 August 2004, Pages 392–399

[3] Culpepper, Martin L., Anderson G., "Design of a low-cost nano-manipulator which utilizes a monolithic, spatial compliant mechanism", *Precision Engineering*, Volume 28, Issue 4, October 2004, Pages 469–482

[4] T. Deng, K. K. Varanasi, M. Hsu, N. Bhate, C. Keimel, J. Stein, M. Blohm "Nonwetting of Impinging Droplets on Textured Surfaces" *Applied Physics Letters*, 94, 133109, 2009

[5] Wang M., Jin HJ , Kaplan D.L, Rutledge G.C., Mechanical Properties of Electrospun Silk Fibers", *Macromolecules*, 2004, 37 (18), Pages 6856–6864

[6] Joh J., Del Alamo J., "Critical voltage for electrical degradation of GaN high-electron mobility transistors", *Electron Device Letters*, IEEE, 2008

[7] Del Alamo J., "Nanometre-scale electronics with III–V compound semiconductors", *Nature*, Volume 479, 17 November 2011, Pages 317-323

[8] Radhakrishnan, R. and Trout, B.L. "Order parameter approach to understanding and quantifying the physico-chemical behavior of complex systems," in *Handbook of Materials Modeling*, Part B, Chapter 5: Rate Processes, Section 5.5, Dordrecht, The Netherlands: Springer, 2005

[9] MIT-Norvatis Center on Continuous Manufacturing. URL: http://engineering.mit.edu/research/labs_centers_programs/novartis.php, accessed January 3, 2013

[10] Swiston, A.J., Gilbert, J.B., Irvine, D.J., Cohen, R.E., and Rubner, M.F. Freely, "Suspended Cellular "Backpacks" Lead to Cell Aggregate Self-Assembly", *Biomacromolecules* 11, 1826-1832, 2010

[11] Shah J., Breazeal C., "An Empirical Analysis of Team Coordination Behaviors and Action Planning With Application to Human-Robot Teamwork", *Human Factors*, 52(2), 234-245, 2010

[12] Arana, L.R.; Schaevitz, S.B.; Franz, A.J.; Schmidt, M.A.; Jensen, K.F.; , "A microfabricated suspended-tube chemical reactor for thermally efficient fuel processing," *Microelectromechanical Systems, Journal of* , vol.12, no.5, pp. 600- 612, Oct. 2003

[13] Chung, S.Y., Bloking, J.T., Chiang Y.M., "Electronically conductive phospho-olivines as lithium storage electrodes", *Nature Materials*, 1, 123 – 128, 2002

[14] David J. Bradwell, Hojong Kim, Aislinn H. C. Sirk, and Donald R. Sadoway, "Magnesium–Antimony Liquid Metal Battery for Stationary Energy Storage", *Journal of the American Chemical Society*, 134 (4), 1895-1897, 2012

[15] Sarma, S.; Brock, D.; Engels, D.; , "Radio frequency identification and the electronic product code," *Micro, IEEE* , vol.21, no.6, pp.50-54, Nov/Dec 2001

[16] Moon T.S. , Yoon S.H., Lanza A.M. , Roy-Mayhew J.D. and Jones Prather K.L., "Production of Glucaric Acid from a Synthetic Pathway in Recombinant Escherichia coli", *Appl. Environ. Microbiology*, February 2009 vol. 75 no. 3 589-595

[17] The printed world*, The Economist*, The Economist Newspaper Limited, Date: Feb 10, 2011

[18] Barr, M. C., Rowehl, J. A., Lunt, R. R., Xu, J., Wang, A., Boyce, C. M., Im, S. G., Bulović, V. and Gleason, K. K. (2011), Direct Monolithic Integration of Organic Photovoltaic Circuits on Unmodified Paper. *Adv. Mater*., 23: 3500–3505. doi: 10.1002/adma.201101263

[19] Sheffi, Y., "*Logistics Clusters: Delivering Value and Driving Growth",* MIT Press, ISBN: 9780262018456, September 2012

[20] Gregory, J.; Atlee, J.; Kirchain, R.; , "A Process-Based Model of End-of-Life Electronics Recycling Driving Eco-Efficiency-Informed Decisions," *Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on* , vol., no., pp.138-143, 8-11 May 2006

[21] Gordon, M. "Cramming More Components onto Integrated Circuits," *Electronics Magazine* Vol. 38, No. 8 (April 19, 1965)

[22] URL: http://www.foreignaffairs.com/articles/137602/damien-ma/china-digs-it

[23] URL: http://grad-schools.usnews.rankingsandreviews.com/best-graduate-schools/top-engineering-schools

[24] DARPA Adaptive Vehicle Make (AVM) program: http://www.darpa.mil/our_work/tto/programs/adaptive_vehicle_make__(avm).aspx

[25] Fraunhofer Main Home Page: http://www.fraunhofer.de/en.html , accessed January 3, 2013

[26] AMP Report, July 2012, URL: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf

[27] PCAST Report, June 2011, URL: http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf

[28] IDA Report on Advanced Manufacturing, URL: http://www.wilsoncenter.org/sites/default/files/Emerging_Global_Trends_in_Advanced_Manufacturing.pdf

[29] Make. An American Manufacturing Moment. Report by the U.S. Council on Competitiveness, December 2011, URL: http://www.compete.org/publications/detail/2064/make/

[30] McKinsey Global Institute, McKinsey Operations Practice, Manufacturing the future: The next era of global growth and innovation, November 2012, URL: http://www.mckinsey.com/insights/mgi/research/productivity_competitiveness_and_growth/the_future_of_manufacturing

[31] Hauser D., de Weck O.L., "Flexibility in component manufacturing systems: evaluation framework and case study", *Journal of Intelligent Manufacturing*, 18 (3), 421-432, June 2007

[32] Ahn H.S., Kaminsky P., "Production and distribution policy in a two-stage stochastic push-pull supply chain", *IIE Transactions*, Volume 37, Issue 7, 2005

Appendix I – List of 24 Technology Areas related to Manufacturing

ID	Related Technology
1	Flexible electronics
2	Supply chain and logistics
3	Rapid prototyping
4	Manuf. simulation and visualization
5	Manuf.- pharmaceutical and medical
6	Printed electronics
7	Optoelectronics and photonics
8	Energy efficient manufacturing
9	Precision manufacturing
10	Continuous process control
11	Adaptive and flexible manufacturing
12	Lightweight materials
13	Robotics
14	Material genomics
15	Coatings
16	Composite materials
17	Semiconductors
18	Manufacturing using recycled materials
19	Advanced metrology
20	Manuf. and refinement of biofuels
21	Smart automation
22	Information tech for manufacturing
23	Advanced sensing
24	Meta-materials

Appendix II – Initial Grouping of 24 Technology Areas

Manufacturing Process Innovation
- Rapid Prototyping
- Coatings
- Continuous Process Control
- Flexible Electronics
- Semiconductors
- Printed Electronics
- Manufacturing / refining of biofuels
- Pharmaceutical and Medical
- Optoelectronics and Photonics

New Materials and Multi-Scale Mfg
- Material Genomics
- Composite Materials
- Lightweight Materials
- Meta-Materials

Automation and Precision Manufacturing
- Smart Automation
- Advanced Robotics
- Precision Manufacturing

Manufacturing Systems
- Supply Chain and Logistics
- IT for Manufacturing
- Adaptive and Flexible Manufacturing
- Mfg Simulation and Visualization

Sustainability in Manufacturing
- Mfg using recycled materials
- Energy efficient manufacturing

Measurement and Testing
- Advanced Sensing
- Advanced Metrology