MIT Roundtable: "The Future of Manufacturing Innovation – Advanced Technologies"

March 29th from 2-5pm at MIT's Wong Auditorium, Building E51 (held in cooperation with the Council on Competitiveness)

Participants:

2:00 Introduction – Susan Hockfield, President, MIT

2:05 Framing the Discussion: The Manufacturing Problem – Prof. Suzanne Berger

2:15 The DARPA Perspective: The Pathway for Manufacturing Technology Advance – Ken Gabriel, Deputy Director, DARPA

2:30 Panel One: The Materials and Nano Transformations (8-10 minutes for each presenter)
Moderator – Prof. Angela Belcher
The "Materials Genome" Project - Prof. Gerbrand Cedar
Lightweight Materials for Transport - Prof. Charles Fine and Richard Roth, Dir. Materials Systems Laboratory, re: advanced lightweight materials for heavy equipment and transport
Bio-Inspired Materials - Prof. Christine Ortiz – re: advanced bio-inspired structural materials for engineering
Nano manufacturing - Prof. Martin Culpepper – re: physics-driven invention of tools, technology and techniques that enable practical manufacturing, manipulation and measurement at the small-scale.

3:40 Panel Two: Technology Advances for Transforming Production (8-10 minutes for each presenter)
Moderator – Prof. Charles Cooney
Robotics/AI in Manufacturing - Prof. Rodney Brooks
Production Transformation in the Pharma-Bio Sector - Prof. Bernhardt Trout
The Crossover between Services and Manufacturing – Prof. Sanjay Sarma – pervasive networking of RFID, IT, sensors
Sustainable Manufacturing and Systems – Prof. Timothy Gutowski –

4:50: Concluding Remarks – Putting Advanced Technology Elements in Context – Could they be Part of a Manufacturing Industry Transformation – Prof. Michael Cusumano

5:00 Concluding Comments – Susan Hockfield

MIT Roundtable: "The Future of Manufacturing Innovation – Advanced Technologies"

Introduction

Opening Remarks

Susan Hockfield, Ph.D. *President, Massachusetts Institute of Technology*

Manufacturing innovation is an important subject and it is a delight to host this roundtable. This is the second such roundtable; the first addressed the innovation system overall, while this one is focused on manufacturing, particularly technology advances that could spur manufacturing efficiency and productivity.

We may have the sense that nothing is made in America anymore, but manufacturing is still critical to the U.S. economy. In 2007, the manufacturing sector contributed $1.6 trillion to our GDP. Manufacturing directly employs 12 million people, and an upcoming study suggests another 30 million jobs depend on our manufacturing sector. Not only are these good jobs, but also the health of the manufacturing sector is enormously important for the nation's innovation capacity. U.S. manufacturing firms employ 64% of U.S. scientists and engineers. These scientists and engineers conduct 70% of the research and development conducted in the United States.

The current challenges for U.S. manufacturing are profound. We run a $500 billion trade deficit in manufactured goods and a $50 billion deficit advanced technology goods. That is a $50 billion deficit in the sort of technologies that were invented here in the U.S. Underlying problems—such as those in our automotive sector— have also been compounded by the recent "great recession." It has been estimated that we need to create 17-20 million jobs in the coming decade to recover from the current downturn and meet upcoming job needs. It's very hard to imagine where those jobs are going to come from unless we seriously get busy reinventing manufacturing. No matter how brilliant our innovations, they are not going to translate into strong, durable job growth unless a substantial fraction of these new technologies really is made in America.

Some might argue that this conversation is occurring too late or is pointless because the U.S. cannot compete with low wage, low cost, increasingly advanced economies like China and India. But the examples of Japan and Germany counter this argument. These countries are both high wage, high cost economies like ours, but they each run dramatic trade surpluses. They provide proof that building a strong, advanced manufacturing sector is possible and very much worth pursuing.

It is not a coincidence that our manufacturing challenge in the 1980s came from Germany and Japan. Japan developed a famous manufacturing system with quality awareness built into every step of the process. They established a quality/price tradeoff. They imposed just-in-time inventory practices. They treated employees as a fixed cost, not a variable one.

At the same time Germany created a system of workforce apprenticeship programs and a strong export promotion system. The U.S. urgently needed to respond at that time and MIT faculty stepped up. They analyzed their competitors' advantages and then recommended innovations that would be appropriate in this country to ensure our success. This research produced two very influential books: *Made in America*[1] and *The Machine that Changed the World*[2].

The challenges today are comparable to the 1980s, or perhaps worse. If our manufacturing is going to rise again, it will take an aggressive mix of answers including new processes, new business models, and—unquestionably—new education and training paradigms. But a key hope for progress lies in tapping unprecedented new manufacturing technologies, which is what this roundtable hopes to address.

Four questions to ask at this roundtable are:

- What are the emerging opportunities in manufacturing technologies?
- Can we accelerate their entry and their success?
- What can we at MIT do beyond the individual research projects?
- Particularly, what changes can we recommend to government and industry to create innovation policies that are tuned to the moment?

Hopefully, this roundtable will be only the beginning of a far-reaching effort to re-think America's manufacturing economy, playing a similar role to the landmark National Academy report "Rising Above the Gathering Storm[3]" and its sibling legislation, the America COMPETES Act.[4]

The Manufacturing Problem

Suzanne Berger, Ph.D. *Raphael Dorman and Helen Starbuck Professor of Political Science*

Here are some facts about manufacturing in the United States: The U.S. remains the world's largest manufacturing economy and we produce 22% of the world's manufactured goods. That share has been constant for the past 30 years and China and Japan lag far behind us. What has changed over the past 30 years is the number of Americans that are employed in manufacturing; this number has gone down. Today, manufacturing workers constitute only 10% of the U.S. workforce. This is a big problem. While the U.S. economy created millions of new jobs each year before the recession, it did not create millions of new *good* jobs with wages like those in manufacturing. The average wage of a manufacturing worker in 2008 was $72,000 per year. The average income of a worker in the rest of the economy

1 Dertouzos, M., Lester, R., Solow, R. and the MIT Commission, *Made in America Regaining the Productive Edge*, MIT Press, 1989

2 Womack, J., Jones, D., Roos, D., *The Machine that Changed the World: The Story of Lean Production*, Harper Collins Publishers, 1991

3 National Academies of Science, *Rising Above the Gathering Storm: Energiing and Employing America for a Brighter Economic Future*, 2007

4 The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act of 2007, P.L. 110-69

was about $57,000 a year. A General Motors (GM) worker earned about $27 per hour including benefits, while a Walmart worker earned about $9 per hour.

The decline in the number of manufacturing jobs is also a major problem for the U.S. economy because as large as our share of the world's manufactured goods is, our appetite in the U.S. for manufactured goods is far larger, and the U.S. currently has huge trade deficits. The U.S. has also failed to exploit new opportunities for exporting U.S. goods. Manufactured goods comprise only 60% of U.S. exports, and our ability to manufacture is a powerful determinant of our ability to export to the rest of the world. Finally, our ability to reinvent manufacturing in the U.S. will determine our capability to bring new technologies of enormous importance and promise to the market.

I urge you to think about the widely held view that manufacturing is a sunset industry, bound to decline in numbers and contribution to the economy as productivity in manufacturing increases. This notion of manufacturing as a sector that should be allowed to sink below the horizon has three distinct possibilities:

The first is that, maybe, manufacturing is a sunset industry like agriculture. In agriculture U.S. productivity is so great that Americans really couldn't eat any more food in the U.S. than its farmers already produce. Maybe Americans could eat more high-valued food, but probably not much more overall. Is this an accurate model for thinking about the future of manufacturing? With three TVs and two cars in every American family, can the country not consume any more goods than manufacturers are already producing? This is obviously false. The U.S. imports vast quantities of manufactured goods from the rest of the world, and a cursory look at its trade deficit shows that there’s a lot of room to make more here in the U.S.

A second reason one could think manufacturing is a sunset industry in the U.S. is because it involves a lot of labor, and the U.S. just can’t compete with low-wage countries like China and India—nor would we want American workers earning Chinese wages. But, as economists always remind us, what really matters is not wages but unit labor costs. Unit labor costs are determined by the productivity of more or less qualified workers using more or less advanced capital equipment. Wages are a small part of the overall equation of cost.

Prof. Berger shared one anecdote from an interview with an Italian-owned sweater factory in Romania as part of a globalization project. The manager was so proud of what had been achieved in the sweater factory. She showed Prof. Berger two baskets of beautiful white wool sleeves, one basket made in Romania and one in Italy. Prof. Berger found the two were indistinguishable and thought, this looks like serious trouble for the Italians. The factory manager said “Absolutely not. My Romanian workers are wonderful, but the sleeves cost 50% more to make here than in Italy.” How could that be, when wages were ten times higher in Italy? “Our Italian workers can hear when those machines are about to break and stop the machine before they waste any valuable wool. Italian workers know how to repair the machines so they don’t have to wait two days for a technician. Italian workers know how to reprogram the machines so they can be making sleeves in the morning and other things all day long." We must keep in mind that what really matters is unit labor costs and not wages.

This is a very hard fact for Americans to believe—more so because American manufacturers' first response to virtually any challenge has been to pick up and chase after lower-wage labor. This is a problem the MIT researchers who carried out the *Made in America* project 20 years ago already signaled.

What U.S. manufacturers might have done—and might still do today—is what the Germans have done. That is to address the problem from the other side: to lower the unit labor costs by adding to the qualifications of workers and to raise the profitability of firms by focusing on producing highly valued good with great quality and unique features. In Germany, 22% of the workforce is in manufacturing jobs, hourly compensation is 66% higher than U.S. wages, and they have become an export powerhouse. Germany is not an exception; across Europe wages are on average 20% higher than U.S. wages. The problem is not that the U.S. can't compete with China on low wages. It is that the U.S has not provided its workers with the kind of education that would allow them to make the kinds of goods that Germans make. And the country has not developed enough of the kinds of manufacturing that could generate both high profits and good jobs.

A third possible reason to think manufacturing is a sunset industry is that in this age of networked, globalized economy, the U.S. just doesn't need to be doing manufacturing. The country could focus on branding, R&D and sales, and let the manufacturing take place elsewhere. It is true that in some industries digitization has allowed a virtually complete break-up of the production system, completely separating design and production. Today as the U.S. looks at a range of possible new industries, there are many reasons to question whether manufacturing is just a commodity activity. Above all the U.S. needs to think about the new technologies, new products, and new processes that can already be identified in MIT labs: Can they be brought to the market if new manufacturing industries *cannot* also be developed? That is the issue our speakers will address. We've asked each of them:

- Can we already identify new products and technologies that would require major advances in manufacturing to bring them into the economy?
- Can we identify new manufacturing possibilities that offer the prospect of injecting innovation and growth into the economy?
- What are the national policies that could contribute to transformation in manufacturing and our retaining manufacturing in the U.S.?

Breaking Rules and Making Rules

Ken Gabriel, Ph.D.   Deputy Director, Defense Advanced Research Projects Agency (DARPA)

Both Dr. Gabriel and DARPA director Regina Dugan feel very strongly about this roundtable's topic. They both worked at DARPA, then started companies, then returned to

DARPA in their current positions. They view DARPA's manufacturing initiative as so important that it cuts across all offices and programs in the agency.

DARPA has a particular way of making advances in technology, and manufacturing is no different: *creative destruction*. The title of this presentation is "Breaking Rules and Making Rules" because that is what really goes on in manufacturing. If you look at the history of manufacturing, there is a lot of this creative destruction. An old manufacturing approach gets wiped out and a new one takes its place, but there will always be manufacturing. The challenge is to stay ahead of the curve, to make sure you are always exploiting the next generation of manufacturing technology, to make sure you are the one making the new rules.

DARPA was created in response to Sputnik. The U.S. was caught by surprise, and DARPA was created to make sure that would not happen again. DARPA's charge was, in particular, to make sure not only did the U.S. prevent surprise, but that it also created surprise. DARPA' successful model is frequently emulated. One of the key reasons for this success is their remaining capabilities oriented, as opposed to technology oriented. DARPA is not investing in manufacturing technologies *per se*, but focusing on what the desired outcome is. That is the heart of what distinguishes DARPA from other funding agencies in Washington.

Dr. Gabriel presented two plots: one showing cost per unit of military aircraft over time, which showed rapid increase. Projecting forward, this trend indicated that by 2054 one plane would consume the entire U.S. defense budget. This is clearly not a sustainable trajectory. The next plot showed the development time of a product vs. the number of parts it contained, and plotted data from integrated circuit manufacturing and aircraft manufacturing. Integrated circuits take roughly the same time to develop now as they did decades ago, even though modern chips have millions of times more parts. For aircraft, the development time increased rapidly with increasing complexity, with the next generation strike fighter expected to take 220 months of development. Not only does this explain the trajectory of costs shown on the first plot, but it also points to a major problem: threats 220 months from now are not going to be the same as they are today; the strike fighter's development cycle is much longer than the threats' development cycle.

Why are aerospace systems growing that way, while integrated circuits are staying flat even while complexity is skyrocketing? It is the result of a fundament decision made early on. The semiconductor industry won't bother to make a product if it will take longer than 24 months to develop, because anything longer than that will render the product obsolete by the time it is ready to sell. Market pressures will kill it off.

What makes it harder to make an electromechanical product? What makes it so hard to make an airplane? Part of that difficulty and the increased complexity is "crossing seams." Manufacturing as it is practiced today usually starts with design, then a prototype, then limited production, then high volume production, than quality assurance/quality control, then deployment. Every time you cross a seam between one of those stages, there is an opportunity for risk, cost, and time because you may need to change something and go back a stage. Change is not good. You have to be very careful about managing change. When you cross a boundary, such as limited production to high volume production, you generally change tools, processes, materials, etc. and each of these changes can cause problems.

There have been many advanced manufacturing initiatives and the like over the last 20 years. What were they doing? Why didn't they solve these problems? Most of these projects were focused between the seams, improving each stage without fixing the problems associated with crossing the seams. Is it instead possible to avoid the seams? Eliminate prototyping and low volume manufacturing and create science and technology solutions that make it feasible to produce volumes of *one* in large-scale manufacturing?

But that is what the semiconductor industry had already done. Thirty years ago, the oncoming crush of complexity was clear, and one of the industry's solutions was to decouple design from manufacturing. They made a tradeoff, giving up some component performance in favor of ease of design. This "heresy" created an explosion in semiconductor products, in productivity of designers, and opened up design from a few hundred to tens of thousands of designers, ultimately changing the business model for how semiconductors are made. Not all industry and manufacturing will look like semiconductor fabrication, but there are some ideas here that might be useful in other types of manufacturing. These principles open up a manufacturing technology to far greater numbers of people, allowing productivity and innovation to become much more important than wages or labor cost.

This does not just work in electromechanical production, but in biological manufacturing as well. DARPA has a program called "The Accelerated Manufacturing of Pharmaceuticals" (AMP) program, within the Advanced Manufacturing Initiative. This started as a program to counter bio-threats. As such, the program could not assume it would know in advance what it had to counter. The goal was the capability to counter a threat assuming access only to its DNA, so it could handle any synthetic pathogen. Because of their capability-oriented approach, they were led to a solution fundamentally different than the traditional way of making vaccines, which takes millions of chicken eggs and six months. The approach in this program hijacked the protein synthesis of tobacco plants and in one month the plant could be harvested and processed, and the protein vaccine produced. This process is very similar to the semiconductor model just discussed, as it is capability oriented and uses abstracted design rules supplied by biology.

It is important to look at the *entire* manufacturing chain: design rules, manufacturing technology, qualifications, all the way to validation. This case in point, the AMP program was to be the government's backup response to the H1N1 virus in case it resorted and the threat changed. Six months for a normal vaccine would have been too long to counter such a threat change. The problem with the AMP solution was in the validation: The new vaccine would be ready in a month, but Food and Drug Administration (FDA) approval for the new process of making it would take two years. AMP is working with the FDA now to fill out that complete solution. Apple provides another example of how to do this well. The iTunes apps store contains 150,000 applications, yet a new application waits less than five days to be tested, qualified, approved, and put in the iTunes store. If it took three months, the whole business model would collapse. In closing, as the country considers various approaches to manufacturing and innovation, it must keep in mind the mundane but important things, because without them there will be no forward progress.

Panel 1: Materials and Nano Transformations

Introduction

Angela Belcher, Ph.D. Germeshausen Professor of Materials Science and Engineering and Biological Engineering

Research in materials science can impact many current challenges. New findings can lead to advances in energy, medicine, transportation, technology, and the environment. It is an exciting time to be in this field. The speakers on this panel will share innovative ideas to make and transform materials in manufacturing.

Nanotechnology, as pioneered by Richard Feynman in his 1959 talk, "There's Plenty of Room at the Bottom," is based on the ability of nanomachines to manufacture products with atomic precision. Understanding and harnessing this approach offers enormous potential. Bringing atoms together in tight spaces can change their physical properties to produce new and advantageous effects. However, many of these interactions are unknown, and the field still has tremendous room for growth with sufficient investment in R&D.

The United States' leadership in nanoscience R&D in the last ten years was possible because it possessed the best education in nanoscience and engineering in materials science. The U.S. maintains this competitive advantage, but other countries are catching up.

MIT has been at the forefront of nanoscience research in the U.S. The MIT environment has generated incredible advances in nanoscience by fostering interdisciplinary and cross-disciplinary collaborations. Researchers from biological and chemical sciences, along with multiple engineering disciplines, operate under the common idea of nanoscale approaches, and pursue understanding at multiple centers around campus. These centers—the Institute for Solar Nanotechnology, funded by the U.S. Army, the Center for Materials Science and Engineering, funded by the National Science Foundation (NSF), and the Center for Cancer Nanotechnology Excellence, funded by the National Cancer Institute (NCI)—have changed the education model across disciplines at MIT, and stand as an example to other research institutions.

"Materials Genome" Project

Gerbrand Cedar, Ph.D. R. P. Simmons Professor of Materials Science and Engineering

Professor Cedar opened with the example of hydrogen energy to highlight the importance of materials science in enabling technological innovation. Despite the potential for producing energy from hydrogen, the lack of good materials to produce, store, transport, or use this energy prevent its implementation. These problems may prove insurmountable, thereby neutralizing a promising technology.

Given that new materials facilitate new technologies, inefficiencies in their commercialization inhibit innovation. On average, 18 years elapse between the discovery of a new material and its commercialization. This lag occurs because scaling up the use of the material exposes nuances of its properties that must be confronted after significant investments have already been made. Initial material selection, then, plays a critical role in the product development timeline.

A method to predict material properties would inform the materials selection process, and could dramatically reduce the product development timeline. The ability to design materials computationally, analogous to virtual airplane design, has enabled rapid technological advances. For example, the world record lithium ion battery took two years to design and then one year to construct. The ability to design materials enabled the speed of this progression.

The Materials Genome Project will facilitate further technological advances by providing physical properties for materials on a large scale. By predicting these properties using computational approaches, this project will reduce the time dedicated to materials discovery and change the nature of the design process. Information is already available for 30,000 inorganic compounds, and many more organic ones, which has already enabled technological advance.

The infrastructure for this approach took three years to create, but now enables discovery to occur in matters of weeks. Efforts to identify lithium-ion battery cathodes using this database highlighted a completely new class of materials in only four weeks. Construction took another three weeks, producing a material with improved performance that had no equivalent in known chemistry.

This process has been used in a range of applications, including thermoelectrics, photovoltaic materials, and mercury adsorption from coal gasification. If we can scale up computing to prescreen materials, they can be virtually designed to optimize performance, reducing the time to production and allowing people to focus their concentration on other areas of the design process.

Lightweight Materials for Transport

Charles Fine, Ph.D. — *Chrysler LFM Professor of Management*
Richard Roth, Ph.D. — *Director of Materials Systems Laboratory*

Lightweighting of vehicles offers a lucrative opportunity for manufacturing innovation. Higher manufacturing costs will be offset by increased product efficiency, providing both high wages and increased spending power domestically. It offers a versatile approach to combating our reliance on foreign oil, but needs a strategic vision for implementation.

Although it presents technological and economical challenges, successful vehicle lightweighting could provide lasting benefits to the U.S.

By reducing the weight of motor vehicles, lightweighting reduces their energy requirements. This would decrease energy consumption from any fuel source used to power a vehicle. For gasoline-driven vehicles, lightweighting will produce increased fuel efficiency. Lightweighting will have the added advantage of compatibility with advanced powertrain and electric vehicles, facilitating their incorporation into vehicle design.

Lightweighting will require a redesign of the entire manufacturing supply chain. The new processes this requires will not be easily copied, which could create a distinct first-mover advantage. High up-front costs discourage the introduction of this approach. The steel industry has a huge head start in manufacturing, preventing the easy adoption of lightweighting technologies.

The semiconductor industry in the 1980s demonstrates that an appropriate strategy can produce economic success under these circumstances. At that time, collaboration between major manufacturers and the federal government coordinated the supply chain to leverage the scale and scope of the semiconductor industry as a whole. This approach engaged the entire value chain, built parallel and interlocking roadmaps across the industry, and built consensus around common vision and leadership. The automotive industry may be in a position to engage in a similar approach with regards to vehicle lightweighting.

Adopting this approach will benefit domestic manufacturing. Current technologies can already be applied to vehicle lightweighting, but additional development will create dramatic improvements. Developing the subsystem protocols needed to implement vehicle lightweighting will provide the U.S. with significant advantages over foreign countries. Lightweight vehicles will therefore be an exportable good, and work to reverse country's deficit in manufactured goods.

In response to a question from the audience, Professor Fine stated the government should incentivize fuel economy to facilitate these objectives through measures such as a fuel tax.

Bio-Inspired Materials

Christine Ortiz, Ph.D. *Associate Professor of Materials Science and Engineering*

Researchers can use principles inspired by biology to improve material properties. Biological materials are designed to be high strength, lightweight, and penetration resistant, and to resist particular types of loads. Materials have inherent physical properties. Combining these with morphometric principles learned from comparative and evolutionary biology, and principles from architecture and manufacturing creates hybrid principles of universal design. Incorporating these principles into manufacturing allows the amplification of mechanical properties and functional specificity found in natural systems.

For example, natural exoskeletons provide an appealing system to evaluate by this approach. Through understanding of the properties of naturally occurring exoskeletons that provide dynamic flexibility, resistance to extreme conditions, or important optical properties, and integrating these properties into new materials, we can manufacture enhanced protective equipment for military use.

New technical processes allow us to reverse engineer these natural systems. CAT scans provide three-dimensional structural information about natural systems. Plaster reconstructions then create the structures we model. Moving forward, technological advances will enable this process at the nanometer scale. For example, laser beam melting of layered metal sheets can construct three-dimensional structures with increased precision and decreased scale. This provides a more versatile materials platform than current approaches that use ceramics or other biological polymers, and an innovative approach to manufacturing.

Nanomanufacturing

Martin Culpepper, Ph.D. *Associate Professor of Mechanical Engineering*

Industrial manufacturing processes require extensive technological support. The current dearth of hardware support for nanomanufacturing inhibits process development. Common technology modules and manufacturing principles operating on general hardware components are needed to enable an efficient transition from laboratory discovery to full-scale manufacturing. We need a better understanding of nanoscale tools and technologies before we can efficiently integrate new discoveries into factory level manufacturing.

For example, the understanding of manufacturing principles has enabled dramatic cost reduction in a manufacturing technology that writes biological molecules onto a solid surface. Through evaluation of the component requirements compatible with technology, the machine costs can be decreased 100-fold. In turn, this allows us to array multiple implements to increase speed. Other advances similarly decreased costs and increased efficiency, culminating in an economical device with important industrial applications.

Unfortunately, the skills required to achieve this are difficult to acquire. Six of the eight researchers involved in this project in the Culpepper Laboratory earned B.S. and M.S. degrees from MIT, and are working towards their Ph.D. Advanced technical skills must be developed as part of the curriculum to enable further advances in nanomanufacturing. This emphasis will produce improved understanding of nanomanufacturing principles and provide increased opportunities for their implementation.

Five 'T's will advance nanoscale manufacturing:

- Theory – the basic processes.
- Tools – the equipment necessary to implement the theory.
- Techniques – the processes necessary to implement the theory.

- Training – the people necessary to enact these.
- Transfer – essential for connecting research and development.

To implement this theory in a manufacturing context, we need better tools for research and for education, and to continue to support theory research. Introducing the tools and techniques in an educational context is important in training students in the field. Training students requires a large investment, and it is important to keep students in the field. The ability to go efficiently from the lab to industrial manufacturing requires coordinated improvements in these areas.

In response to a question from the audience, Professor Culpepper emphasized the importance of educating students in driving the field forward. He recalled his astonishment at the education systems in Asian countries that emphasized manufacturing technologies and suggested that the American education system focus more resources in the field.

Panel 2: Technology Advances for Transforming Production

Introduction

Charles L. Cooney, Ph.D. *Robert T. Haslam Professor of Chemical Engineering*

The first panel discussed how science is creating new products and processes. Product design and manufacturing processes are intrinsically linked, and that may be the real opportunity moving forward. There are, however, three thoughts to keep in mind. First is that the U.S. thinks of manufacturing as a commodity, but there is nothing commoditized about new technologies like those discussed by the first panel. Second is that innovation is not concentrated in one field or geographical area; it emerges from many smaller pieces to form a manufacturing "ecosystem." Finally, the U.S. needs to consider design for the entire product life-cycle, while remaining aware that situations change and that plans will need to be adjusted accordingly. To gain sustained competitive advantage, the country needs to understand how these technologies come together into new manufacturing strategies.

Robotics and Artificial Intelligence in Manufacturing

Rodney Brooks, Ph.D. *Chairman and CTO Heartland Robotics Inc.*
Panasonic Professor of Robotics (on leave)

Low-cost manufacturing has always followed the cheapest labor, from Japan and Korea following World War II to China and more recently Vietnam. Much of this labor is "robotic", meaning that simple tasks are endlessly repeated. Many of these tasks could be achieved by industrial robots. Investments in automation technology could bring low-cost manufacturing back to the United States.

Industrial robots have been used since 1961 at General Motors. These systems perform repeated motion with incredible precision, but lack programmability and adaptability. As a result, integrating a robot into a manufacturing process can cost ten times as much as the robot itself. Advances in microprocessors, networking, and sensor technologies could be used to create more flexible robots that could be adapted to specific purposes. This would make automation a more viable approach for the tens of thousands of manufacturing companies in the U.S. with revenue less than $10 million. Combining this with the sort of national marketplace made possible by the Internet could dramatically change the way the U.S. thinks about manufacturing.

Parallels can be drawn with personal computers. The computer industry took off when computers reached a usability threshold that made them universally accessible. A similar trend is occurring with robots, which the U.S. military is rapidly deploying, and which are appearing as consumer products like iRobot. It is important that the country enable a sort of bottom-up approach because top-down approaches can't deal with the operational uncertainties; you need engineering to look at particular operations.

Specific recommendations are 1) use DARPA and the National Institute for Standards and Technology (NIST) to support innovative low-end manufacturing, 2) have the Occupational Safety and Health Administration (OSHA) take a lead by tracking new automation technology and quickly approving new practices, and 3) incentivize companies that bring manufacturing into the U.S. Developing new tools and deploying new processes will also both require increased support for Science, Technology, Engineering, and Mathematics (STEM) education in the U.S.

Transforming Pharmaceutical Manufacturing

Bernhardt Trout, Ph.D. *Professor of Chemical Engineering*
Director, Novartis-MIT Center for Continuous Manufacturing

Traditional approaches to pharmaceutical manufacturing are very inefficient. The operational asset effectiveness is often only 20-30% of its capacity, compared to 80-90% in most manufacturing industries. For investments worth $100 billion that adds up to a large loss. In addition, the manufacturing process is subdivided into steps that occur in different places. Overall there has been no new technology introduced in years for manufacturing small-molecule drugs (note: this is not the case for production of biological pharmaceuticals).

There are several reasons that manufacturing innovation has stalled in this arena. First, regulations are extremely conservative. Talented engineers are not inclined to work in an environment where innovation is discouraged. Second, the profit margins for pharmaceutical manufacturing are high, and manufacturing is a small part of the total cost. Third, many drug companies see their core business as marketing and supply, as well as providing financial support to take drugs through clinical trials. In some sense, large pharmaceutical companies have become essentially financial enterprises, using mergers and acquisitions to get licenses for new compounds then outsourcing the manufacturing. This strategy produces short-term gains, but it isn't good for innovation.

The industry has also seen a lot of outsourcing. Pharmaceutical manufacturing has moved to low-tax countries like Ireland and Singapore. Puerto Rico used to be a destination for pharmaceutical manufacturing, until it raised taxes. Pharmaceutical companies have, however, begun to take interest in developing new manufacturing systems. The Novartis-MIT Center for Continuous Manufacturing is an example. This is a $65 million investment by Novartis in fundamental manufacturing research. The goal is to think about how the industry should look in 10-15 years, and then figure out how to get there. As an added benefit, we at the Center think the complexity of high value-added technology will force companies to invest in new technology in the U.S.

The government has a long history supporting innovation in manufacturing, and it should continue to do so. MIT and Novartis are working with the FDA to streamline regulatory processes. Tax incentives could also help keep more manufacturing in the U.S.

Logistics for Local Manufacturing

Sanjay Sarma, Ph.D. *Associate Professor of Mechanical Engineering*
Director, MIT-SUTD Collaboration

This talk is really a plea for research on manufacturing systems. The industrial revolution, followed by development of standardization and mass-production systems, has made manufacturing so good that anyone can do it. Now we have a global supply chain and manufacturing diffuses very quickly. This diffusion is particularly driven by labor costs and salaries. We find that engineering salaries are high in the U.S., and they fall off as you move farther away; in fact, the curve almost looks like a parabola as you move away from the U.S. At the same time, transportation costs increase as you start to move production away from the point of distribution. That flattens out after a short distance, so that going farther does not increase the costs.

Could the U.S. flatten out this curve? One way that others have discussed doing this is making high-tech products because technology takes time to diffuse. This could be a fundamental way for the U.S. to stay competitive. Brand strength is another way, similar to machine tools in Germany. Local subsidies and emphasis on sustainable manufacturing could also bring production to otherwise high-cost areas.

The thing I really want to talk about is transportation and logistics costs. Of course it costs less to make something in Chicago if you want to deliver it to Chicago, but because of economies of scale it is often cheaper to make things far away. The problem with local manufacturing is terrible logistics. You don't get economies of scale if you are shipping small quantities, like less than a truckload (LTL). To really change the cost-curve for local manufacturing we need innovations that make small-lot logistics more economical.

Sensors, automatic warehousing, and LTL management are all approaches that can benefit local manufacturing. The clothing manufacturer Zara provides a great example. By manufacturing with family cooperatives in Spain they are able to change styles very quickly. Another example of a local company is KIVA Systems, started by MIT graduates, that uses networking and sensors to build automated warehouses. Logistics is a science that can fundamentally change the economics of local manufacturing. The government should take systems research seriously, with investment and maybe subsidies for companies that are innovating in these technologies.

Systems for Sustainable Manufacturing

Timothy Gutowski, Ph.D. *Professor of Mechanical Engineering*
Director, Laboratory for Manufacturing and Productivity

In manufacturing, we take resources from the environment, put them through some transformations, and put out some sort of emissions. Throughout this process we tend to undervalue ecosystem services. Even once we realize they aren't free, it is difficult to give them a price. It is a fundamental problem that underpriced ecosystem services provide both competitive advantage and an incentive to over-exploit. Addressing this problem requires governments to cooperate before they even start thinking about competition.

We can address sustainability problems in several ways: more efficient processes, finding alternative resources, and "end of pipe treatment" to reduce emissions. Industry over the last thirty years has already been consuming a decreasing fraction of energy in the U.S. Even when efficiency goes up, it is often matched by a larger increase in output, so that total resource use still increases. Manufacturing is already sensitive to price of inputs so the easiest improvements are not there. We can do better to improve transportation and building efficiency.

What are some ways to address a problem like the Intergovernmental Panel on Climate Change (IPCC) carbon target of reducing CO_2 emission to 50% of 2000 levels by 2050? If the U.S. can't make policies that reduce demand for energy then it has to hit more stringent targets in other areas. The country will also have to encourage investments in efficiency to avoid "carbon leakage", where high-emission activities move to places with cheaper energy.

The U.S. needs to discuss technology evaluation. Many proposals for energy reduction are themselves energy-intensive technologies. This can only work with great care. Technologies need to be evaluated for their *total* effect on the planet, instead of within narrow boundaries or under favorable conditions. Technologies need to be designed for sustainability, use interdisciplinary teams, and analyzed in terms of the full production system and product life-cycle.

Sustainability is a vague term that needs to be more clearly defined. Once a clear problem is identified, we can consider building solutions into products and systems from the beginning. We need to make sure, however, that there is international cooperation and a level field for competition.

Questions

Q. Much of the conversation has focused on bringing mass production back to the U.S. What are your thoughts about creating a new manufacturing system based on customized products?

A. (Trout) Greater personalization is a trend that everyone sees in pharmaceuticals, but little is being done about it in industry. Some of the things in the Novartis-MIT Center for Continuous Manufacturing get at this by understanding processes at a very basic level. This will allow us to design customized products more easily.

A. (Brooks) We've already seen programmable robots that make customizable parts. When we get more robotic assistance you could imagine individual workers being more like craftspeople. I think we'll see this trend over the next several decades.

A. (Sarma) It's also the supply chain that is geared to mass manufacturing. The U.S. Postal Service is a good example of a one-to-one supply chain. If we could really make small supply chains work it will make mass customization a lot more possible.

Q. Recycling will have great impact on competitiveness. Can we design products so that they can easily be taken apart?

A. Europeans talk about "re-provisioning", thinking of products as a source of materials for other products. Some industries, like plastic, could do much more to encourage recycling.

Q. Are laboratories at the university or manufacturing facilities working on doing production with local resources, to be more "in harmony" with nature?

A. (Gutowski) One of my suggestions is having concurrent research teams checking each step against the big picture throughout the development processes. Engineers are not used to thinking in these terms. For example, making carbon nanotubes is extremely energy-intensive, but none of the engineers I know working on them even consider energy. In the lab, the cost of energy is less than 1% of their total cost.

Concluding Comments

Michael Cusumano, Ph.D. *Sloan Management Review Professor in Management*

The principles discussed are acted upon quite well by American companies and American universities. Why we have experienced difficulties over the last few years is a complicated issue. Japan is not a good model; it has been in the doldrums for 20 years, and its massive surplus is due to lack of consumer spending and constraints on consumers. China is also not the model because it is focused on low cost manufacturing. China's future depends on how well they develop their universities, because as we've seen in the roundtable's panels, most of the new industries we see come out of science or advanced engineering. If you don't have that, you will have troubles in the future. This is one of Japan's major problems as well, because their universities are still not what we have in the U.S. or Europe.

There are six principles really driving competitive firms and industries. The first is the importance of "platforms, not just products". Developing a whole ecosystem of innovation around a product is important. Microprocessors give rise to all kinds of software; the Google portal creates a whole set of industries working off its technologies. These are platforms, not just one-off hit products. The second principle is "services, not just platforms." That is to say, services connected to these platforms. The value of a cell phone is far more in the services and content that the cell phone generates than the phone itself. Even automobiles generate far more revenue from different kinds of services (e.g., leasing, repair, maintenance, insurance).

The next four principles are fairly commonly talked about in management, but they are no less important. Again, they apply to what we do well. The next principle is "capabilities, not just strategy." We train the best Masters of Business Administration (MBAs) in the world, but ultimately you need unique design, engineering, or service innovation capabilities. At the university level, the U.S. is the best in the world. More worrisome is what we are putting into those universities: our secondary education system is a major issue. We need to figure out how to nurture the new industries being created by our science and engineering capabilities. The "pull don't push" principle is about creating direct connections from your operations to the market or customers. This includes just-in-time production, agile product development, and prototype driven development. Again, we do this quite well.

"Scope not scale" is the fifth principle. This is almost obvious; if scale were most important, GM would have been the most profitable manufacturing company for the last half century, and it wasn't. Economies of *scope* are about being able to leverage different kinds of products and services using common components, not wasting technologies or people, nor having redundancies, but meeting the needs of different customers and segments effectively. Avoid being preoccupied with scale. The last point is "flexibility not just efficiency," which is similar to "scope not scale." Do not become overly preoccupied with efficiency, but rather think about what we actually need to do to change, adapt, and lead new markets. American organizations, managers, and universities are among the most flexible in the world, so we do have tremendous capabilities to adapt.

There are also some temporary pendulums that go back and forth: One of China's major advantages is that they undervalue their currency. If the Yuan floated to its actual value, we would see a change there, like we saw with Japan 20 years ago. We worked on the value of the Yen then, which changed things dramatically. Government should work on the value of the Yuan now. It is also a major problem and a great pain to us in the Sloan School of Management that half our students go to Wall Street. Hopefully we can change that again.

It might be time to revive initiatives like "Leaders of Manufacturing" that encouraged our best students in engineering and management to go into companies that really built things. Still, all of the pieces are there. These principles lead to a newer way of thinking about management principles. They have great relevance for transforming how we think about management in the future. The older way of focusing on creating the best product you can and having strategy oriented to pushing technologies to market at maximal scale worked in the past, but it's time to move to another level. It's time to focus on making products into industry-wide platforms, generating an array of services around them. Many American companies already do this today—Microsoft, Intel, Apple, Google, Cisco, Qualcomm—so in general we should take an optimistic view of what we can do. Everything from today's roundtable feeds into this. We have to worry about focusing only on what we're good at, rather than what the markets need, but most of us do see visions of the future that fit into the capabilities we have and continue to create.

This summary of the March 1st, 2010 MIT Innovation Roundtable was written by the following members of the MIT Science Policy Initiative:

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