

Advanced Technology and the Future of U.S. Manufacturing

Proceedings of a Georgia Tech research and policy workshop

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Preface

Philip Shapira, Jan Youtie, and Aselia Urmanbetova

Attention to the technological capabilities of U.S. manufacturing is enduring theme for business and policy. Since early industrialization, U.S. manufacturing competitiveness has been founded on the development and adoption of advanced technologies, innovative processes, and novel management practices. In recent decades, concerns about global competition, the pace of innovation and discovery, and the prospects for industrial jobs and skills have stimulated further efforts to look to technology as a remedy to sustaining the position of the U.S. as a competitive base for manufacturing.

Traditionally, policy-makers view manufacturing from the view of jobs, production, and trade balances. From this perspective, the current state of American manufacturing raises concerns. In particular, U.S. manufacturing lost 2.8 million jobs in the period 2001-2003, while its manufacturing trade deficit with the rest of the world has continued to grow. These developments reflect a mixture of cyclical and structural trends. For example, we know that manufacturing employment tends to increase during economic expansions and decrease during downturns. Indeed, during the 1990s economic upturn, U.S. manufacturing employment grew from 16.8 million jobs in 1992 to 17.3 million jobs in 2000, but then fell to 14.5 million jobs in 2003. We also know that the modern peak of manufacturing employment was 19.4 million jobs – achieved almost a quarter of a century ago in 1979. Yet, while these headline job numbers indicate that U.S. manufacturing sector employment has significantly declined since the beginning of the 1980s, the underlying story is more complex. Over the long run, U.S. manufacturing output and productivity have both increased tremendously – primarily because of enhancements in technological capabilities. Real output per hour per worker in American manufacturing was more than four times greater in 2000 than fifty years earlier. However, manufacturing's share of total U.S. economic output (measured as a proportion of gross domestic product) has consistently declined, from about 30 percent in 1950 to 15 percent in 2000, due to the great expansion of service sectors. At the same time, it is also clear that in the 21st century, these statistical categories are less coherent now than they were in the middle of the last century. Manufacturing today involves significant contributions from activities counted in the services sector, including research, development, engineering, finance, advertising, maintenance, logistics, and other business-oriented functions. It is also worth noting that long-run employment losses in manufacturing coupled with increased productivity have been experienced not only in the U.S. but in most other industrial countries, as well as in developing countries (including, surprisingly, China). Moreover, we are now increasingly appreciative that service jobs, like their manufacturing predecessors, can be outsourced too.

As we reflect on such current trends and seek to think forward, it seems that the future of manufacturing in the United States will hinge increasingly on capabilities to develop, deploy, and commercialize new products, processes, organizational structures, human skills, and management practices. And all this is in the context of increasingly capable international competition and globalization of trade and technology. To be sure, the innovative American “factory” of the future will surely not look like the large American factory of the 1950s, with its assembly-line processes and cadres of routine shop-floor and administrative workers. But what

will the American factory of the future look like? What will be its innovative edge, and what systems of research, production, supply, and distribution will it use? And, who will work in it?

To try to answer these kinds of questions, we assembled an interdisciplinary group of leading researchers at Georgia Institute of Technology (Georgia Tech) in January 2004. Coming from fields which included science and engineering, management, economic development, and public policy, we asked the group to stretch beyond the short-term business cycle and the immediate economic issues – to discuss and debate longer-run opportunities for manufacturing in the United States and to consider the role that advanced technology and innovation might play in creating this future. We challenged workshop participants with this set of specific questions and issues:

- What are the next generation manufacturing technologies? How have technologies evolved to date, how might they emerge in the future? Who are among the leaders in the research, development, and application of these technologies?
- What are the potential impacts of next generation technology on future U.S. manufacturing capability? How can these technologies be used to enhance manufacturing competitiveness and to sustain the manufacturing base in the United States?
- How will next generation technologies change the profile of what we know today as manufacturing industry? What will be the impacts on direct and indirect labor? On advanced service inputs? On the form and attributes of manufactured products? On suppliers? On what we consider as manufacturing enterprise? On value-added services associated with manufactures?
- To what extent can small and mid-sized manufacturers benefit from these future technologies? How can existing SMEs enhance their competitiveness through these technologies? What are the potentials for new small firm start-up ventures?
- To what extent can traditional industries (e.g., textiles, pulp and paper) benefit from these future technologies? How can traditional industries enhance their competitiveness through these technologies?
- What organizational structures need to be in place for these technologies to be widely adopted or leveraged to enhance competitiveness? What changes are needed in management strategies?
- What impact do these technologies have on the future manufacturing workforce? Does adoption of new technologies always mean fewer manufacturing employees? What human capabilities and skills will the future manufacturing workforce possess?
- To what extent will next generation manufacturing technologies be successfully implemented in the United States? What are the risks that these technologies will be implemented elsewhere? What kinds of linkages U.S. manufacturing need to establish with other global manufacturing locations to best take advantage of next generation technologies?
- What are the constraints and threats to the adoption of next generation technologies?
- What public policies, relationships, and programs need to be in place to address constraints and threats and to foster the adoption of these technologies?

The papers and discussion comments contained in these proceedings summarize the various ways in which workshop participants responded to these questions. No participant was able to address all issues in a single presentation, but collectively the workshop shed significant light on the posited questions and indicated a series of current and prospective technological

opportunities, strategies, and challenges for U.S. manufacturing. After an opening review of five decades of studies on US manufacturing and technological opportunities, panelists presented papers on future trends and impacts of a series of emerging technologies in manufacturing as well as on issues of manufacturing organization, logistics, and workforce. These presentations are included in the proceedings, along with summaries of discussion comments.

The workshop was held at Georgia Tech on January 30, 2004, as part of a project on U.S. manufacturing trends that a team of researchers from SRI International and Georgia Tech are undertaking for the National Institute of Standards and Technology (MEP, Manufacturing Futures Group). The Georgia Tech team was led by Professor. Philip Shapira (School of Public Policy) and Dr. Jan Youtie (Economic Development and Technology Ventures). We gratefully acknowledge support from the Manufacturing Extension Partnership (MEP) Program of the National Institutes of Standards and Technology, under award number SB1341-03-Z-0014. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and discussants and do not necessarily reflect the views of the MEP.

Summary

In January 2004, an interdisciplinary workshop was held at Georgia Institute of Technology (Georgia Tech) which brought together a group of eighteen researchers, policy analysts, and technology program managers to examine the potential impacts and trajectories of advanced emerging technologies on the future of U.S. manufacturing.

The group considered a range of next generation emerging manufacturing technologies, including nanoscience and its applications in microelectronics and medicine and new developments in rapid prototyping, machine tools, distributed production and supply chain technologies, and logistics. These emerging technologies were discussed in the context of the current and anticipated position of U.S. manufacturing in the global economy and the sector's current and prospective challenges and opportunities. Additionally, participants explored the implications of these technologies for new forms and modes of business operations, internal and external business linkages, supply chains, and educational and training programs.

Drawing on historical as well as current developments, workshop participants discussed issues about how these technologies will affect the workforce, whether public policies adequately respond to technological opportunities, and what types of programs should emerge to advance technological developments and enhance their impact on U.S. manufacturing and business operations.

In the opening paper of the workshop, "A Brief History of the Future of Manufacturing: U.S. Manufacturing Technology Forecasts in Retrospective, 1950-present," Professor Philip Shapira of the Georgia Tech School of Public Policy reviewed past manufacturing technology forecasts over the last five decades. This paper was co-authored with Jan Youtie, Aselia Urmanbetova, and Jue Wang. Shapira observed that new technology has frequently been seen as both a remedy and a threat: in the manufacturing sector, it has aided substantial improvements in manufacturing productivity and quality, yet at the same time it has generated concerns about impacts on the number, type, skill requirements, and location of manufacturing jobs. Currently, the technologies anticipated to be influential in the future of manufacturing include molecular and nano-manufacturing, biomaterials and bio-processing, microelectromechanical systems, free-form fabrication, and new software control technologies. However, it was noted that predictions as to how technology will evolve in future periods have had mixed records of fulfillment. Some manufacturing technologies have not fulfilled expectations (e.g., integration technologies in the 1980s) whereas others have greatly exceeded expected adoption rates (e.g., the Internet in the 1990s). Moreover, technology forecasts did not occur in a vacuum; they were always conjoined with projections about how to manage these technologies, global responses to these technologies, and the impact they will have on employment and skill. Here, Shapira noted the emphasis on innovation, knowledge management, customer relationships, and life-cycle waste reduction as among the organizing concepts expected to be prominent in the future period.

The ways in which manufacturing systems have changed in the past and are likely to change in the future were discussed by Steven Danyluk, Director of the Georgia Tech Manufacturing Research Center and Professor of Mechanical Engineering in his paper on "Technological Opportunities to Develop New Capabilities: Manufacturing, Strategic Engineering, Adaptive

Technologies, and Controls.” The three most significant trends are: (1) movement away from mass production towards semi-customization, (2) shifts away from centralized production location towards distributed production sites, and (3) transformation of centralized business control towards corporate collaboration between production sites. These changes have been anticipated by the research community, which has responded by investigating how manufacturing could embrace advances in molecular sciences, and how the new forms of manufacturing could be enhanced by intelligent web-based data management systems that embrace supply chain systems within and between complex multi-site manufacturers.

A new vision of engineering was offered by Farrokh Mistree, Georgia Tech Professor of Mechanical Engineering, in “Strategic Engineering on the Integrated Design of Products and Processes.” Mistree argued that strategic engineering is a comprehensive approach for designing products and processes that efficiently and effectively accommodate changing markets and associated customer requirements, and technological innovations in a collaborative, distributed environment while safeguarding the economic viability of a company. Additionally, strategic engineering considers global outlook. The main requirements for successful strategic engineering are people who are highly trained in traditional engineering-related sciences and well-versed in disciplines that enhance one’s ability to evaluate the general trends and needs of manufacturing within the governmental and global contexts.

New products and processes may change the roles of traditional consumers and producers, according to Professor David Rosen of the School of Mechanical Engineering and the Manufacturing Research Center at Georgia Tech in “Additive Manufacturing Technologies: Opportunities for Customization, Flexibility, Complexity, and Simplicity.” Additive manufacturing (AM) is the usage of layer-based “rapid prototyping” (RP) technologies for manufacturing. Additive manufacturing, through customized geometry and functionality, makes it possible for end users to participate in the design of fully customized products such as hearing aids, dental alignments and other dental restorations, eye glasses and lenses, and joint replacements. In the near-term, new AM applications will continue to take advantage of the shape complexity capabilities for economical low production volume manufacturing. Longer timeframes will see an emergence of applications that reflect more functional and material complexity. As AM technologies improve, the number of machines will increase and their costs will decrease. Since AM technologies are capable of fabricating complex shapes and potentially highly functional devices, it becomes possible to embody an entire manufacturing system within a single, small machine. Rosen predicts that AM machines will begin to be used in the home in less than 10 years.

Professor of Mechanical Engineering Steven Y. Liang, in “Future Trends in Machine Tools and Controls and their Potential Impacts on U.S. Manufacturing,” outlined the challenges currently faced by the U.S. machining tools industry. The U.S. has experienced the world’s largest drop in machine tool production, almost 36% from 2001-2002, which occurred in parallel with a significant decline in R&D spending. Liang suggests that U.S. machine tooling can be sustained through increased research and development in areas such as precision cutting, microscale free-form magnetoabrasive machining, and microscale machine tools. Increased collaborations between industry, government, and academia could result in further new technology, new product, and new process technologies for the machine tool industry.

Moving to the world of micro- and nanotechnology, Jim Meindl's "Technological Prospects for Microelectronics" described the future prospects of microelectronics in one word: nanoelectronics. Meindl is Professor of Electrical and Computer Engineering and Director of the Microelectronics Research Center at Georgia Tech. Drawing the analogy of steel as the major structural material that drove the industrial revolution, Meindl pointed to the importance of silicon as the principal material of the information revolution in the second half of the 20th century. The advances of the last four decades enabled improvements in silicon microchip production by one trillion times with virtually constant costs. Meindl's expectation is that, with continued transistor size reductions and increases in silicon wafer diameter, by 2020 there will be chips containing one trillion transistors. This will become possible when the 100-nanometer minimum feature size is reduced to 10 nanometers within the next 20 years. The challenge for U.S. silicon manufacturers is to maintain their primary position in innovation and development.

Zong Lin Wang's paper "What is Nanotechnology? And How Will This Small Wonder Make a Big Change in Manufacturing?" conceptualized nanotechnology as based not only on nano-size but also on size-induced novel, unique and significantly improved physical, chemical, and biological properties, phenomena, and processes of materials and systems. Wang is Professor of Materials Science and Engineering and Director of the Georgia Tech Center for Nanoscience and Nanotechnology. Wang observes that these distinctive nanoscale properties make nanomaterials very different from materials observed and manipulated at larger scales. Nanotechnology could impact the production of virtually every human-made object – from automobiles and electronics to advanced diagnostics, surgery, advanced medicines, and tissue and bone replacements. By using structures at nanoscale as a tunable physical variable, we can greatly expand the range of performance of existing chemicals and materials. Entirely new biological sensors based on self-assembled monolayers can facilitate early diagnostics and disease prevention of cancers. Switching devices and functional units at nanoscale can improve computer storage and operation capacity by a factor of a million. Nanomanufacturing technologies are produced using massive parallel systems via self-assembly. Current research focuses on using nanoscience to discover new materials, phenomena, characterization of tools, and fabricating nanodevices. Nanomanufacturing represents the future impact of nanotechnology for human civilization. For successful implementation, nanomanufacturing needs standardized measurements at the atomic level molecular-scale manipulation and assembly, and micro-to-millimeter-scale manufacturing technologies.

Traditionally, manufacturing has been viewed as an engineering field. Nanomanufacturing requires capability beyond engineering in fields such as mechanics, electrical engineering, physics, chemistry, biology, and biomedical engineering. Thus nanomanufacturing requires not only innovative research and development, but also a new educational system for training future scientists and engineers.

Professor Rina Tannenbaum of the Georgia Tech School of Materials Science and Engineering in her paper on "Advances in Materials and Self-assembly" described self-assembly as the process of starting at the nano level and building up to the micro level. Small changes in size at the nanoscale can produce large changes in reactivity and chemical properties of materials, which leads to selective depositing of material-specific functional group characteristics that can

be used for molecular recognition in a variety of ways. Three main areas for future applications (1) nanocomputers that utilize nanotubes as interconnections replacing today's transistors, (2) controlled drug delivery, and (3) optoelectronic materials that are created out of block of polymers. Nanoscale manufacturing faces several challenges to produce these future applications including providing for special manufacturing environment equipment; meeting high costs of maintenance, equipment, and raw materials; controlling for production time horizons (some nanoscale processes can take days or weeks); developing quality control mechanisms or enhancing ability to fix problems in small scale; and defining ways to integrate small nano devices into macro world.

In "Medical Devices and Global Manufacturing," David Ku indicated that medical devices constitute the largest industry group within the entire medical technologies sector, accounting for \$40 billion in value globally with half of that attributed to the United States. Ku is Regents Professor of Management and Mechanical Engineering at Georgia Tech. He observes that the medical device industry's complex production processes favor manufacturing locations in high-wage regions, particularly those with well-established metalworking capability, although future materials innovations may impact this linkage between metalworking and devices. Devices that are less invasive, more cost-effective, and require shorter recovery and rehabilitation time define the future of the medical device industry to the extent that manufacturing systems capable of producing highly-customized products for different types of populations come to fruition.

Chip White, Professor in the Georgia Tech School of Industrial and Systems Engineering, drew on his paper "New Opportunities in Logistics: Technology and Trucking" to portray developments in trucking logistics technologies and the challenges that emerge from different adoption levels. The U.S. trucking industry transports more than three-quarters of the freight in the country. There are two main forces that drive the industry: the 1980's era just-in-time manufacturing that requires higher time and load precision on the part of carriers, and the 2000's era just-in-case policies to meet sudden supply chain disruptions. Additionally, trucking companies have to meet regulations in emissions, ergonomics, and diesel fuel. The operating environments undergo tremendous shifts for the driver, the fleet manager, and the firm as new technologies are offered. Many of these new technologies address security, emissions, ergonomics, fuel efficiency, and information and communications areas. Fleets differ in their levels of technology adoption and utilization. Adopting a technology before the fleet and the firm is ready for it can be as detrimental as waiting too long to adopt it. The challenge of the future for the trucking industry is to incorporate technological advances at just the right time so that the benefits from the use of technology can be fully accrued, but not so late as to lose competitive advantage.

In presenting his work "Futures for Traditional Industries: Strategic Issues in the Pulp and Paper Industry in Georgia" with Alan Porter and Alisa Kongthon, Charles Estes emphasized the importance and relative weight that traditional industries still have in the U.S. economy. Estes is Manager of the Traditional Industries Program with the Georgia Tech Economic Development Institute. Faced with declining demand and employment, such traditional industries as pulp and paper, textiles and carpet, and food processing, are becoming key focal points for local and state governments in their effort to maintain dynamic/healthy employment and output growth within their constituencies. Georgia's Traditional Industries Program (TIP) is one such policy effort.

Overall, the TIP program receives about \$3.4 million a year to fund about 40 research projects annually that address common issues and encourage innovation in pulp and paper, textiles and carpet, and food processing sectors. In the case of the pulp and paper industry, there are about 550 mills employing 175,000 workers in the U.S. that generate \$100 billion in shipments or 30 percent of global production. In Georgia, pulp and paper accounts for about \$10 billion in annual shipments and 30,000 employees. The U.S. pulp and paper industry faces increasing cost-based competition in a mature, slow growth, high capital intensive environment. More and more of these firms are consolidating to maintain production output and profitability. It is important to be able to apply technological innovation not just to high tech firms, but also to these traditional industries. The paper describes a forecasting and planning process that identifies research that results in more cost-efficient production processes, reduction of environmental byproducts, and biotechnology-generated replacement of virgin pulp.

Public Policy Professor Cheryl Leggon's "Human Side of Manufacturing Technology: Demographic Changes, Training Needs and Skill Gaps" pointed out that it can be difficult to predict workforce needs because technological forecasts are not always accurate. Given that the workforce is becoming more diverse (with higher percentages of women and minorities), is aging (as the baby boomer cohort approaches retirement), and will be affected by some varied degree of technology-induced job dislocation, Leggon makes the case for restructuring training to instill more specialized skills, capabilities to work in an environment that requires flexibility, and transferable competencies.

In his role as a discussant, Professor Robert McMath of the School of History, Technology, and Society at Georgia Tech employed an historical perspective to identify three themes emerging from the workshop. The first theme deals with mass customization and flexible manufacturing. McMath notes that flexible production recalls the manufacturing modes used prior to the first industrial revolution that were based around "communities of practice" working in a common industry and location. The second theme addresses the need for leadership—a new type of engineer—capable of realizing the promise of nanotechnology to create the next technological revolution in much the same way that past leaders utilized technology to foment the first industrial revolution. The third theme has to do with consideration of the social and policy impacts of technological progress. Technology is typically associated with a reduction in labor and increased emphasis on research and development capabilities. The need for policies to assist the rest of the workforce in making employment transitions is heightened against the backdrop of concern about global competition, outsourcing production, and the current downturn in the manufacturing sector.

In summary, the workshop highlighted several paths for manufacturing's technological future in the United States. To fulfill increasing demand for widescale product customization, manufacturing is becoming less vertically centralized and integrated and more widely distributed. Managing and coordinating production in this environment has the potential for stimulating a range of technologies such as Web based intelligent systems and technologies in the logistics area to deal with security checks, emissions, ergonomics, fuel efficiency, and information and communications. Future opportunities lie in creating the services as well as the technologies to accomplish this management and coordination function.

A second path is focused on high value niche areas for manufacturing. The medical devices industry is an example of a high margin business that manufactures with higher wage, skilled U.S. workers that can work with sophisticated equipment to fulfill stringent quality standards. It is interesting that today's medical device companies depend on traditional technologies and skills in the metalworking sector, even as the industry is among the current and future users of additive manufacturing technologies that apply rapid prototyping and stereolithography to create highly customized products. The future of manufacturing will also rest on the ability of future high value niche areas to be identified, innovated, and exploited.

The third path places attention toward revolutionary opportunities generated by advances in nanotechnology. Highly miniaturized, functional, and efficient electronics devices, and precise and selective biomolecular materials are part of this future. At the same time, it is not yet well known how to manufacture nanomaterials and how to integrate nano- and large-scale manufacturing. Advancing these developments depends on the ability to foster multidisciplinary interconnections between researchers in a range of scientific and engineering disciplines, business managers, policy makers, and educators. A new type of engineer that combines generalist, leadership, and technical capabilities is envisioned to provide a bridge between business, policy, and technical worlds.

History has shown that technological outcomes are not always easy to forecast, witness 1980s-era predictions about the fully automated and integrated shop floor. Nevertheless it does appear that there are a set of next generation technologies around mass customization and flexible production, high-value niche areas, and nanotechnology that have the potential to sustain and advance U.S. manufacturing in the future. This workshop raised an important risk to the ability to advance these technologies in the United States. Global competitors are also working in these same technological areas. In addition to industrialized nations, countries such as China and India are developing very competitive indigenous research, engineering, education, and training capabilities.

Innovation and discovery alone are not sufficient to implement next generation manufacturing technology in the United States. The workshop highlighted the need for organizational strategies, structures, leadership, and workforce training to bridge fields, provide linking services, and make the interconnections necessary to commercialize and upgrade these technologies. Policies and programs are essential to transferring new soft practices, as well as relevant next generation technologies, to traditional industries and SMEs. Workshop participants agreed that it is vitally important that such frameworks of supporting factors and policies are put in place to ensure that next generation manufacturing technologies are not only developed but effectively deployed in the U.S.

Participants in the Workshop on Advanced Technology and the Future of US Manufacturing¹

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¹ The workshop was held at the Economic Development Institute, Technology Square, Georgia Institute of Technology, January 30, 2004.

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A Brief History of the Future of Manufacturing: U.S. Manufacturing Technology Forecasts in Retrospective, 1950-present

Jan Youtie, Philip Shapira, Aselia Urmanbetova, and Jue Wang¹

1.1 Introduction

Since the days of Eli Whitney and the emergence of the “American system of manufactures” in the early nineteenth century, U.S. manufacturing competitiveness has been founded on the development and adoption of advanced technologies, innovative processes, and novel management practices. Attention to the technological capabilities of U.S. manufacturing has continued as an enduring theme through to the present. Indeed, in recent decades, concerns about global competition, the pace of innovation and discovery, and the prospects for industrial jobs and skills have stimulated many efforts to look to the future and the promise of technology as a remedy to sustaining the position of the U.S. as a competitive base for manufacturing.

This paper examines a series of forecasts about manufacturing technologies and business practices from the 1950s forward to today. This brief history of manufacturing’s anticipated future is offered to provide context – and perhaps some moderation – to current assessments about the relationship of new technology and manufacturing. As is often the case in technological forecasting, a look back over the last five decades confirms that there have been many widely anticipated technologies that have resulted in unfulfilled expectations. In other cases, the pace and extent of adoption for some technologies has greatly exceeded initial expectations. For example, the 1980s promoted intensive expectations about the integration and control of shop floor functions, which did not come to fruition to the extent predicted (i.e., fully automated factories). On the other hand, early predictions about Internet technologies were far outstripped by rapid rates of email, Web, and network adoption, which in turn has led to significant changes throughout all aspects of the manufacturing process. A similar transformational trajectory is foreseen in recent predictions about nanotechnology and biological materials; this molecular perspective on materials has now supplanted the chemical view of future materials (i.e., polymers and ceramics) that was dominant in 1980s-era forecasts.

We begin the paper by first offering a summary overview of long-run output, share of value-added, productivity, and employment trends in the U.S. manufacturing base. This is followed by a discussion of selected technology forecasts and predictions in reports published in successive decades from 1950 through to 2000. The publications that we discuss in the paper were identified, in part, through search terms such as the “future of manufacturing,” “future factory,” “critical technologies,” “next generation manufacturing,” “technology foresight,” and “technology road mapping.” We focused on publications with relatively near term forecasts (10 years or less), rather than highly futuristic predictions. The publications’ analyses and

¹ Jan Youtie is a Senior Research Associate in the Economic Development Institute at Georgia Tech. Philip Shapira is a Professor in the School of Public Policy at Georgia Tech. Jue Wang and Aselia Urmanbetova are Ph.D. students in the School of Public Policy at Georgia Tech and research associates with the Georgia Tech Policy Project on Industrial Modernization.

predictions, summarized in Appendix 1 (at the end of this paper) are organized into five main areas: economic environment, current manufacturing technologies, predicted future manufacturing technologies, management practices, and workforce trends.

1.2 Developments in the U.S. Manufacturing Base: the Long Run

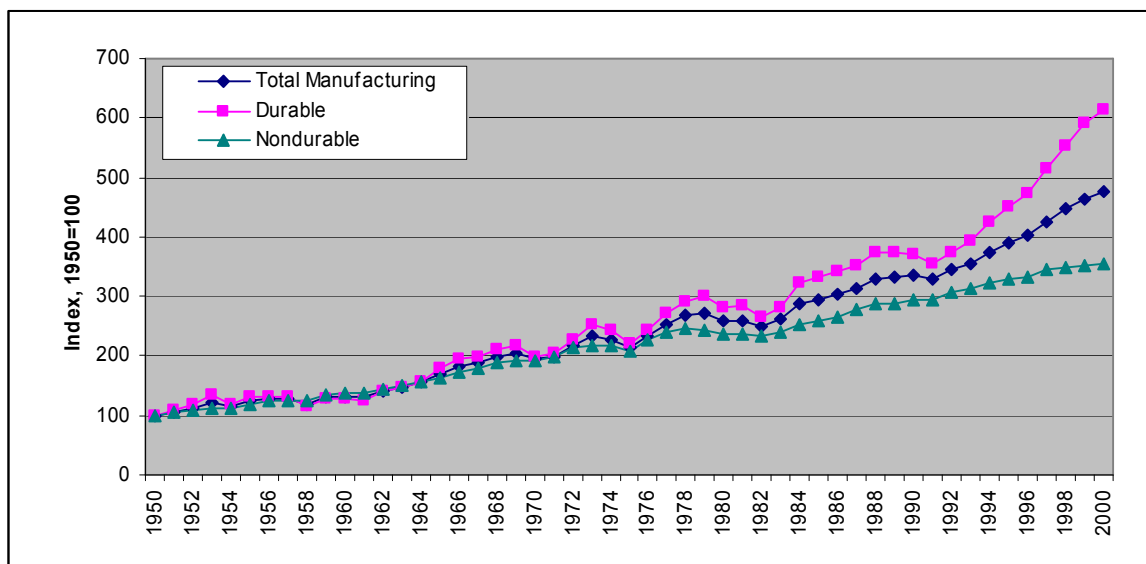
The loss of 2.7 million manufacturing jobs in the last three years (Bureau of Labor Statistics, 2004) has focused attention on the sharp short-term decline in U.S. manufacturing employment and output since the start of the economic downturn in 2001. However, viewed over the long-run, the picture is more complex. In fact, manufacturing output has increased considerably in the second half of the twentieth century. Manufacturing output (inflation-adjusted value of industry output) in the U.S. has increased in every one of the last five decades through to 2000 (Table 1). The 1960s was the decade of the largest average annual percentage growth in manufacturing output, followed by the 1970s and 1990s. Since the 1960s, average annual growth in durable goods (which includes metal and wood products, machinery, cars, and electronics) has outpaced the growth of non-durable goods (which includes food, textiles, apparel, paper, chemicals, and plastics). This difference was especially marked over the last decade. In 1990, the difference between durable and non-durable output, indexed to 1950, was only 78.4 index points; by 2000, durable output had outscored non-durable output by 260 index points (See Chart 1).

Table 1. Manufacturing Output, Productivity, and Employment

(Average Compound Growth Rates for the Decades)						
	1950s	1960s	1970s	1980s	1990s	2000s
Output						
Total Manufacturing	2.95%	4.94%	3.75%	2.81%	3.73%	-2.70%
Durables	2.76%	5.98%	4.67%	3.18%	5.30%	-3.20%
Nondurables	3.27%	3.95%	2.60%	2.25%	1.99%	-2.20%
<u>Productivity (output per hour)</u>						
Total Manufacturing	2.07%	2.78%	2.85%	2.85%	3.78%	4.14%
Durables	1.27%	3.21%	3.30%	3.40%	5.00%	4.73%
Nondurables	3.09%	2.63%	2.45%	2.05%	2.54%	3.14%
Employment						
Total Manufacturing	1.00%	2.08%	0.95%	-0.45%	-0.24%	-5.84%
Durables	1.57%	2.57%	1.42%	-0.66%	0.10%	-6.46%
Nondurables	0.24%	1.34%	0.19%	-0.12%	-0.77%	-4.80%
Services	2.27%	3.44%	3.22%	2.67%	2.22%	0.29%

Output and productivity indexed to 1992 dollars. Source: U.S. Bureau of Labor Statistics.

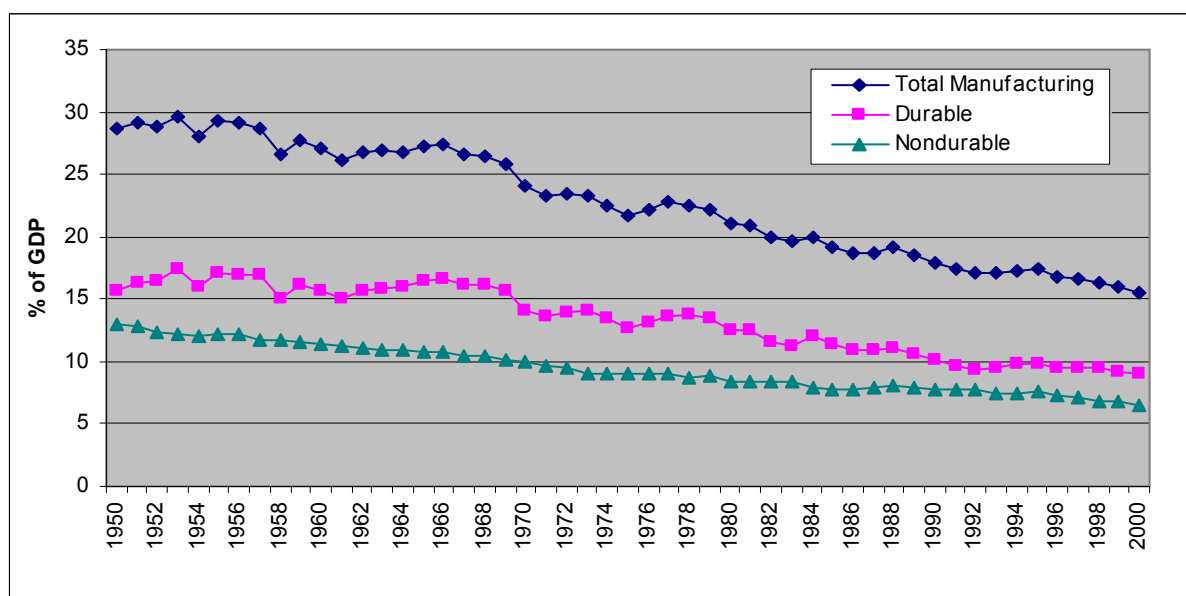
Chart 1. Manufacturing Output Index, 1950-2000



Source: U.S. Bureau of Labor Statistics. 1950 manufacturing output = 100.

Despite the large growth in real output in the U.S., the manufacturing sector's share of the whole economy (manufacturing value-added measured as percentage of the total gross domestic product or GDP) decreased from almost 30% in the 1950's to only 15% in 2000. In this most recent year, durable goods accounted for about 10% of the U.S. GDP, while non-durable goods contributed a little over 5%, with both showing consistent declines in their share of the national economy in every one of the past five decades (See Chart 2). In other words, while the real

Chart 2. Manufacturing Share of U.S. Gross Domestic Product (1972 SIC basis), 1950-2000



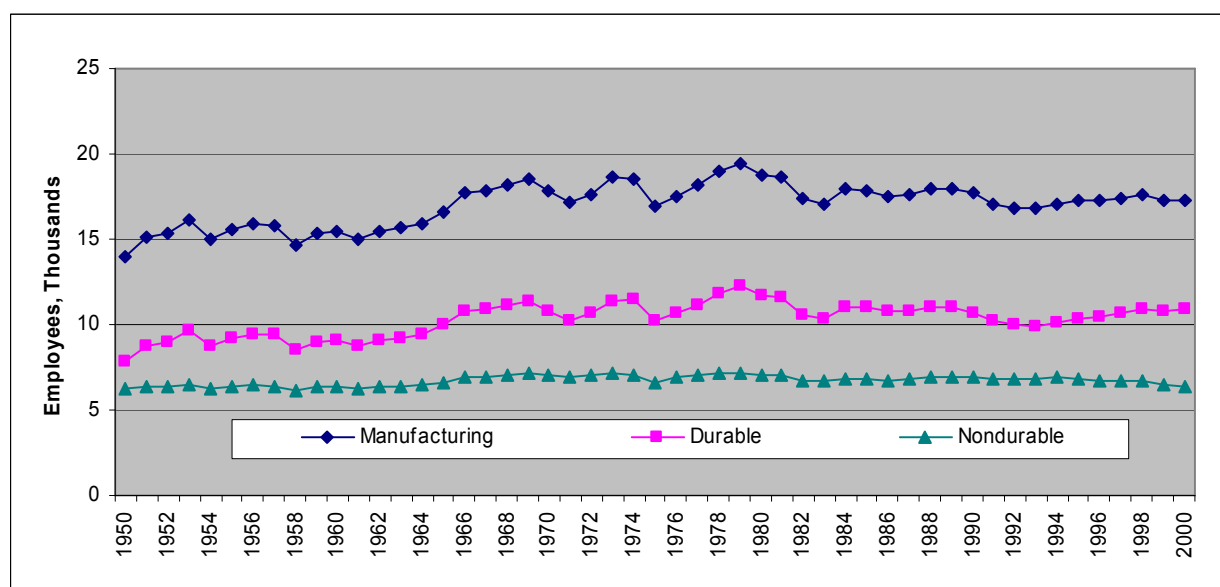
Source: Bureau of Economic Analysis.

value of manufacturing output has grown over the past half-century, manufacturing's share of the overall economy has declined as non-manufacturing sectors – particularly in “tertiary” sectors such as trade, transportation, business, financial, and consumer services, education, and health – have grown even faster.

There is ongoing debate about the causes and implications of this shift in the structure of the national economy. Some analysts argue the declining share of manufacturing and the rising share of services in GDP reflects a long-term transition towards a knowledge-based, post-industrial or services society (Bell, 1973). Others suggest that manufacturing remains a fundamental driver of economic and technological development, but that today many activities integral to modern manufacturing (such as research, design, business service inputs, logistics, marketing, training, and maintenance) are now carried out in businesses that are counted in services sectors (Cohen and Zysman, 1987; Office of Technology Assessment, 1990).

While debate continues about the “boundaries” of modern manufacturing, it does seem clear that employment within the officially-defined manufacturing sector peaked in the late 1970s. Manufacturing employment generally moved upwards from the 1950s through the 1970s, with the greatest job increases occurring in the durables goods industries during the 1960s. By the 1980s, manufacturing employment remained relatively flat with the exception of economic cycles such as employment gains in the 1990s associated with durable goods industries (See Chart 3) or declines in the early 2000s. Employment growth in service industries has consistently exceeded that of manufacturing employment, particularly from the 1970s through the 1990s.

Chart 3. Manufacturing Employment, 1950-2000



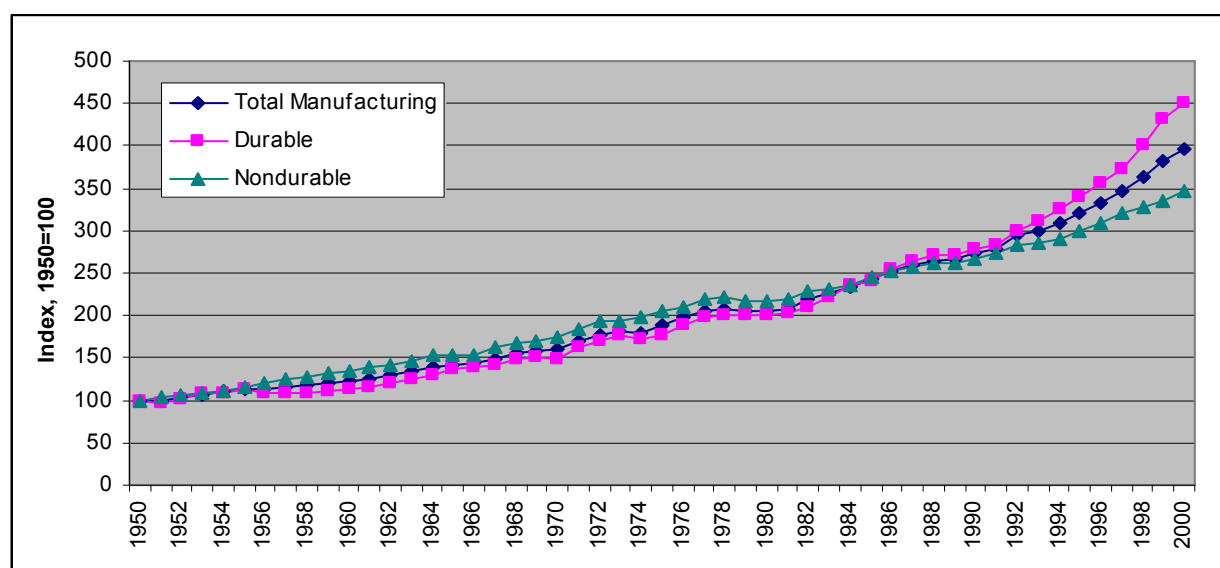
Source: U.S. Bureau of Labor Statistics.

Growth in manufacturing productivity (output per hour) also has followed a significant upward trajectory since 1950s. Productivity growth has consistently risen in the durable goods industries. Non-durable goods also showed productivity gains, although not at an increasing rate such as was the case for durable goods industries. The greatest productivity gains for non-durable goods occurred in the 1950s. Productivity growth rates for durable goods, however, rose

by more than 2.5% between the 1950s and the 1960s, and again by about 1.5% between the 1980s and the 1990s (See Table 1 and Chart 4).

Finally, in this section, we note briefly that perspectives on the composition of the manufacturing workforce also have differed significantly from the relative homogeneity of the 1950s to today's ethnically diverse workforce. Table 2 shows that from 1965 to 1985, the percentage of women in the manufacturing workforce increased by more than 5%. The percentage of female employees has held steady since that time, and the percentage of black employees has similarly held steady since 1975. However, the percentage of Hispanics in the workforce rose by nearly 5% from 1985 to 2000. As a result of these trends, the current manufacturing workforce includes a larger share of females, blacks, and Hispanics than was the case in the 1950s.

Chart 4. Manufacturing Output Per Hour Index, 1950-2000



Source: U.S. Bureau of Labor Statistics

Table 2. Trends in Diversity in Manufacturing Employment.*

Manufacturing Employment				
Year	Total (in thousands)	Female %	Nonwhite %	
1955	16,882	27.0%		
1965	18,032	27.0%	8.3%	
1975	19,275	29.0%	10.8%	
Year	Total	Female	Black**	Hispanic
1985	20,879	32.3%	10.0%	7.6%
1995	20,493	31.6%	10.4%	10.2%
2000	19,940	32.5%	10.3%	12.3%
2001	18,970	31.8%	10.1%	12.3%

*Changes in industrial classifications mean some data may not be strictly comparable

**In 1965 and 1975, the percentage of Non-White workers is reported. In subsequent years, the percentage of Black and Hispanic workers is reported.

Source: Statistical Abstract of the United States (various years).

1.3 Five Decades of Manufacturing Technology Predictions

The next sections review historical predictions about the future of manufacturing technological innovations. We have been selective (since there are a large number of studies). This literature is presented on a decade-by-decade basis.

The Nineteen Fifties

The main technological advances forecast at the midpoint of the twentieth century involved improvements in mass production through the application of technologies developed and utilized during World War II.

For example, in the American Management Association's *Toward the Factory of the Future*, computerization and quality processes were expected to be the hallmarks of the future. Future plants were foreseen to be empowered with digital computation, linear programming, inventory control, quality control, and statistical quality control (AMA, 1957, p.22). Automation was also predicted to reduce the rate of consumption of our natural resources, since automation would force a change in the direction of decreasing entropy increase in the system and process (Grabbe, 1957, p.6). There also were forecasts about changes in business processes to optimize automated production systems by splitting production from finance and selling (AMA, 1957, p.22).

Observers pointed toward future challenges in efforts to further automate production. Grabbe (1957, p.7) criticized "black-box" approaches to implementing automated control functions. The costs to design the automatic features themselves were small in comparison to the costs of redesigning the larger surrounding production systems. Diebold (1952, p.59) called

attention to the problem of inflexibility in automating manufacturing systems, particularly for short production runs.

Automation was not viewed as being synonymous with the worker-less factory. Grabbe (1957, p.87) claimed that although automation could relieve man of many monotonous and arduous tasks, it could not supplant the need for human beings to create, design, build, and maintain the equipment. *Toward the Factory of the Future* maintained that although automation might lessen the need for production manpower, it would increase the need for engineers and white-collar workers (pp.22-23). Diebold (1952, p.142) further emphasized that automated factories would not be workerless factories.

The Nineteen Sixties

1960s-era literature focused on automation, its applicability to certain routine processes, and its limitations. In addition, the 1960s placed an emphasis on globalization and the future proliferation of multinational corporations.

Automation: Its Impact on Business and People, 1961. In this book, Walter Buckingham (1961) predicted that automation was most appropriate for process manufacturing, especially continuous process. “Nearly any continuous process can be automatically controlled whereas a non-continuous process can never be fully automated” (p.36). He divided industries into three groups depending on the extent to which automation could be applied: (1) those in which the entire system could be reduced to a continuous flow process (e.g. rubber, telecommunication, fiber and food products); (2) those in which automation was possible but full or nearly complete automation is not likely (e.g. furniture manufacturing); and (3) those in which no significant automation was likely. Buckingham maintained that automation could actually increase operating expenses due to loss of flexibility, increased risks, and time-consuming changeovers (p.75). He noted that to reduce the costs of raw materials, manufacturers of the future would place greater emphasis on the use of manmade gasses, liquids, electric power, and pure compounds and less emphasis on natural products, crude mixtures, and solids. Buckingham expected that automation would increase the geographical mobility of industry and the attractiveness of low cost labor regions. He predicted that middle managers would be partly replaced by the staff programmers, research analysts, and over-all coordinators who would become necessary to aid top management in planning (p.62).

The Age of Automation, 1965. Leon Bagrit (1965) envisioned that automation would result in consolidation of establishments into large corporations. Automation would enable industry to produce more and more goods with fewer and fewer people and establishments. As a result, smaller units could eventually disappear. “In manufacturing industry, automation will even accelerate the disappearance of the smaller units. With full automation, one might expect the industrial giants to reduce these internal pockets of inefficiency and so make the small firm a steadily less important feature of the industrial life of the nation” (p.103). He also raised concerns about job losses, particularly at the lower ends of workforce, as a result of automation. “Many of the people displaced by automation will be the unskilled and semi-skilled, among whom the black form a large part” (p.104).

International Investment and International Trade in the Product Cycle, 1966. References to globalization and multinationals also emerged in the 1960s. Raymond Vernon (1966)

addressed these trends in his theory of product life cycles, which was developed to explain how the United States switched from an exporter of the product to an importer of the product as production became concentrated in lower-cost foreign locations.

Vernon suggested four stages of trade: (1) development of innovative product for domestic market; (2) rapid expansion of domestic market, starting to export; (3) emergence of competitors (home + overseas), saturation of domestic market, importing of lower priced products; and (4) transformation of competition from advanced countries to less-developed countries. Vernon argued that most U.S. companies initially produced new products in America since it was better to keep production facilities close to the market and to the firm's center of decision-making, given the uncertainty and risks inherent in new-product introduction. While demand for a given new product started to grow rapidly in the United States, demand in other countries was limited to high-income groups, which made it not worthwhile for firms in those countries to produce the new product, but necessitated some exports from the United States. Over time, demand for the new product in other countries would grow, making it worthwhile for foreign producers to domestically manufacture for their home markets, which would limit the potential for exports from the United States. As the market in the United States and other nations matured, the product became more standardized, and price became the main competitive weapon. One result was that foreign producers where labor costs were lower than in the United States might now be able to export to the United States.

The Nineteen Seventies

Technological forecasts during the 1970s addressed the rise of the microprocessor and its impact on the shop floor. In parallel, there was a renewed debate about whether technology would "deskill" the workforce or result in more creative and complex work.

Technology, International Competition, and Economic Growth: Some Lessons and Perspectives, 1973. Keith Pavitt (1973) observed that during the 1960s, multinational firms showed a growing tendency to set up component manufacturing and assembly plants in the less developed countries to take advantage of lower labor costs. He claimed such activities would be considerably expanded in the future: "provided that the population has primary education, labor costs are considerably lower than productivity levels by comparison with the advanced countries." Technological progress in the advanced countries would lead to substitution and economies in the use of raw materials, and thereby turn the terms of trade against less developed countries dependent on the export of raw materials.

Evolution of Computers and Computing, 1977. The 1970s saw the rise of the microprocessor and resulting utilization of computers in manufacturing processes. Ruth Davis (1977) envisioned, "By 1980 the number of minicomputers will reach about the number 750,000, and the number of microprocessors will be more than 10 million. They will be so small and so inexpensive for central processing units and logical units that it will be more practical to buy a number of them than to test a single one for reliability." Because of the highly labor-intensive nature of software design, development, and testing, software development costs were predicted to increase along with the absolute costs of software. Davis was troubled that "the really useful and exciting advances in computing will probably only proceed at the same pace as advances in software engineering. And, this will be distressingly slow."

In terms of computer applications, Davis foresaw the use of computer control of continuous and discrete processes and of real and near real-time process. He predicted that the computerization of control process would result both in substitution of computer control for traditional control systems (as is already occurring in automobiles) and in the invention of entirely new processes not previously possible without computer control. Anticipated computer-based applications also alluded to include working robots and space exploration.

The Third Industrial Age: Strategy for Business Survival, 1975. The concept of logistics was suggested in analyses of business globalization issues in the 1970s. Charles Tavel (1975) reviewed three factors that would have a considerable influence on strategic thinking: transportation, computers and communications. He indicated that as travel fares and time declined, distance became less and less of an obstacle, and national borders became less and less of a barrier. Overcapacity and widely fluctuated raw materials prices contributed to multinationals' interest in less developed countries. As a consequence, less developed countries should be able to greatly increase their influence over multinational corporations in the future compared to the period of 1950 to 1970. The increasing bargaining power of less developed countries would have negative effects on either the absolute standard of living or the growth in the standard of living in more developed countries (Mueller, 1975). One of the difficulties in industrializing less developed countries was quality control, problems arising from which could sometimes cost more to address than the assembly itself (Tavel, 1975, p.70). The only effective way to deal with forces relating to overcapacity and raw materials was to have the best processes, which meant having a technological lead over the competition (Tavel, 1975, pp.82-83).

The Coming of Post-Industrial Society: A Venture in Social Forecasting, 1973. The impacts of technological innovations and changing business practices on the workforce were embodied in two countervailing works. Daniel Bell (1973) proposed the notion of the post-industrial society, which dealt with changes in the economy, occupational system, and social structure. The creation of a service economy, the pre-eminence of the professional and technical class, the primacy of theoretical knowledge, and the rise of intellectual technology characterized the post-industrial society (pp.12-13). Bell predicted that manufacturing would grow at much slower rates in the future, so there would be fewer jobs manufacturing things (p.131). Technology would free workers to pursue more creative mental work tasks. Formal hierarchical management organizations would give way to new egalitarian participatory organizational structures in the post-industrial society.

Labor and Monopoly Capital: The Degradation of Work in the Twentieth Century, 1974. In contrast, Henry Braverman (1974) envisaged that trends in business practices would result in the deskilling of the workforce. Braverman contended that large corporations sought to maximize profit by minimizing costs. This led them to use system analysis and other techniques to simplify work tasks, and replace skilled workers with less skilled and less expensive jobholders. As a result, workers would be steadily deskilled and work degraded. Professionals as well as craft workers were subject to these trends.

The Nineteen Eighties

Following the oil shocks of the 1970s, the 1980s was marked by growing concern about the competitiveness of U.S. industry. This concern reflected the rise of strong European performers, but especially the full development of Japan as an advanced manufacturing economy. U.S. companies faced stiff competition in domestic and export markets not only in industries such as textiles, steel, or consumer electronics, but increasingly in complex manufactures such as machine tools or automobiles and in the high technology manufacture of semiconductors and other electronic components. The fact that the toughest foreign competition was based not so much on cheap labor but on the adoption of advanced technology and superior manufacturing techniques struck at the heart of notions of U.S. ascendancy established in prior decades following World War II. For example, in 1986, the Council on Foreign Relations (cited in Vogel, 1986) commented on Japan's growing economic power:

Future historians may well mark the mid-1980s as the time when Japan surpassed the United States to become the world's dominant economic power. Japan achieved superior industrial competitiveness several years earlier, but by the mid-1980s its high-technology exports to the United States far exceeded imports, and annual trade surpluses approached \$50 billion a year. Meanwhile, America's trade deficits mushroomed to \$150 billion a year. By late 1985, Japan's international lending already exceeded \$640 billion, about ten percent more than America's, and it is growing rapidly. By 1986 the United States became the world's largest debtor nation and Japan surpassed the United States and Saudi Arabia to become the world's largest creditor.

Alarm at the position and prospects of U.S. manufacturing led to a fresh round of studies and predictions about manufacturing and technology (as well as new policy initiatives to promote technology transfer and manufacturing competitiveness). Some of these studies are discussed below.

Toward a New Era in U.S. Manufacturing, 1986. The Manufacturing Studies Board (MSB) Report of the National Research Council, *Toward a New Era in U.S. Manufacturing* (New Era report), outlined technologies that were expected to "have major impact on manufacturing competitiveness" (MSB, 1986).

New Era Materials. Metal-based composites, polymer, and ceramic materials were expected to experience future development. Advances in metal-based composites were anticipated in powder metallurgical processing, superplastic forming, alloys, laser welding substituting, warm- and cost-formed steel parts, silicon-based switches replacing iron-based magnetic devices, metal matrix composites with silicon carbide reinforcements, aluminum-silicon carbide in auto pistol ring and crankshaft applications, and nickel superalloy and stainless steel matrix composites strengthened with silicon carbide in power systems.

Polymers and polymer-based composites were expected to replace carbon steel and aluminum in structural and paneling applications in the auto industry, electronic hardware, appliance chassis applications, and home building components. Polymers and polymer-based composites were also expected to be important in the development of new industrial adhesives such as high temperature epoxies, adhesives with greater strength and elastic range, primerless adhesives (e.g., silicon), and faster-curing adhesives (e.g., cyanoacrylates, urethanes).

Ceramics such as aluminum oxide, zirconia, yttria, silicon nitride, and silicon carbide were estimated to play an important role in electronics, particularly optical fiber production, multi-layer ceramic-to-metal interconnecting and mounting packages for integrated circuits, ceramic multi-layer chip capacitors, piezoelectric ceramic transducers, chemical, mechanical, and thermal sensors. In addition to tooling for metalworking and bioceramics for bone replacement, high-tech ceramics were envisioned to be significant in automobile manufacturing: “An almost totally ceramic engine is a major research objective of virtually every automobile manufacturer and should be extant by the early 1990s.” (MSB, 1986, p.81)

Computerization of the Shop Floor. The New Era report discussed utilization of computer-based technologies to automate design, control, and handling functions. The concept of a fully automated factory was also revived through Computer Integrated Manufacturing (CIM).

Developments in microelectronics had a particular impact on the ability to embed intelligence into processing and plant equipment. In the machine tools area, rapid advances to computerized numerically controlled (CNC) machines were predicted for drilling, milling, and boring. It was anticipated that microelectronics, through a combination of flexible fixturing devices and sophisticated smart robots, would be applied to costly manual fixturing functions. Microelectronics also played a role in the advancement of sensors in micromechanics, three-dimensional vision for depth sensing, artificial skin for heat and touch sensing, and a variety of special-purpose sensing devices. The ability to process sensor-generated data was seen to impact very large scale integration (VLSI) for processing data within integrated circuits (ICs), enabling manufacturing at very fine tolerances and very low defect rates. Sixty percent of all smart robots over a 10-year period were predicted to utilize sensors to operate within a closed-loop feedback system that adapted to the changing environment. The lack of standardized universal robot programming languages was viewed as a challenge to contemporary robotics research, however.

In the design area, computer-aided design (CAD) was not a new technology in the 1980's, but its application to manufacturing was relatively novel. It was envisioned that the use of single- and system-process graphic simulation in conjunction with CAD and other design and process technologies would be a promising new area of research. Great hopes also were placed on developments in the field of artificial intelligence (AI) to complement and in some cases even substitute human experts in areas such as chip design, arc welding, painting, machining, and surface finishing:

As human experts with years of experience become scarce, the expert system provides a way in which to capture and “clone” the human expert... In the 1990's, expert systems are expected that will learn from experience; this means that expert systems eventually will be developed for specialties in which there are no human experts... By the year 2000, managers will probably be communicating with their work stations by voice... artificial intelligence technology promises to make it much easier for computers and computerized equipment to be used by personnel not having computer training, such as managers, engineers, and operators on the factory floor (MSB, 1986, pp.101-102).

The introduction of just-in-time manufacturing drove advances in computerization of materials handling and transport equipment and facilities in the 1980s. Further development of automatic guided vehicles (AGV) and automatic recognition technologies was predicted.

CIM received significant attention in The New Era report regarding the need to integrate the newest information technologies into all of the stages of manufacturing processes. Advances in the application of several information enabling technologies were predicted to promote the effective use of CIM: communication networks, interface development, data integration, hierarchical and adaptive closed-loop control systems, modeling and optimization techniques, and flexible manufacturing systems. It was noted that despite U.S. leadership in the introduction of flexible manufacturing systems (FMS) in 1972 Germany and Japan outpaced the United States in applying FMS across industries, which provided sizeable cost savings to manufacturers in those countries.

Quality-Based Practices. Although The New Era report did not specifically mention the Toyota system, it did predict that several of the principles inherent in this system would impact the future culture of the shop floor. These included increased employee empowerment; coordination of design, manufacturing, purchasing, marketing, accounting, and distribution; cross training; and utilization of information to track quantifiable improvements and performance. Adoption of these cultural changes was envisioned to “at best, proceed in fits and starts” as management, workers, unions, subcontractors, and other groups react to these changes.

Design and Analysis of Integrated Manufacturing Systems, Compton, Dale W., Ed. National Academy of Engineering, 1987. This book was a collection of articles presented at the 1987 National Academy of Engineering Conference entitled “Design and Analysis of Integrated Manufacturing Systems: Status, Issues, and Opportunities.” The primary purpose of the Conference, as identified by Dale Compton (1987), was to explore the status of integrated manufacturing systems design and analysis tools, and identify issues that arise in the use of these tools in designing and later in controlling these systems. The book focused largely on the future of integrated manufacturing. It criticized existing manufacturing technology as being too segmented. Integrated manufacturing, “collaborative manufacturing” and “simultaneous engineering” were distinguished as being more collaborative in nature, requiring greater technological coordination from design labs to factory floors to shipment decks.

The book predicted that flexible production equipment would be more widely adopted in the future given the increased pace of international competition and the shortening of product life cycles. This would be particularly true for the electronics industry, which at the time of the book’s publication had an average product life cycle of 18 months. Another forecast was that cost reduction measures inherent in inventory management, along with systems to carefully synchronize supply and demand, would be critical for future competitiveness. Information technologies were expected to provide not only analytic capabilities but also greater predictive power, as manufacturing moved away from trial-and-error methods toward “a priori” approaches.

Made in America: Regaining the Productive Edge, 1989. The book was the result of the MIT “Commission on Industrial Productivity,” which portrayed a gloomy outlook for the U.S. manufacturing productivity for the 1990’s. The report was drafted over a two-year period and focused on eight industries: automobiles, chemicals, commercial aircraft, consumer electronics, machine tools, semiconductors, computers and copiers, steel, and textiles. For the purpose of a detailed analysis, the Commission visited more than 200 companies and 150 plant sites simultaneously conducting over 500 interviews with the U.S., Japanese and European companies.

The report outlined six problems which deteriorated productivity performance: (1) outdated strategy geared to standardization and mass-production, (2) focus on short-term profits rather than long-term investments, (3) technological weakness in development of new products and technologies, (4) weaknesses in general education and vocational and on-the-job training, (5) failures of cooperation and stakeholder fragmentation, and (6) lack of governmental encouragement and investment.

As summarized by Michael Dertouzos (1989), the report proposed five imperatives for improving productivity: (1) developing new fundamentals of manufacturing such as organizational and technological excellence (vs. short-term financial performance), (2) fostering a highly-educated workforce through greater job security and on-going job training, (3) developing a working blend of individualism with cooperation, (4) opening further to international markets, and (5) gearing macroeconomic policies towards better general education and financial security that would foster greater long-term investments.

The Nineteen Nineties

The 1990s are marked by a highly concerted effort on the part of the governmental agencies to analyze the conditions and investigate strategic potential of the U.S. manufacturing in general. The concern over the success of Japanese and German manufacturers in the early part of the decade pushed government and industry to seek new business and product alternatives. Manufacturing business practices had to be re-conceptualized to incorporate many Japanese management notions.

Government and industry directed specific attention towards the development of new technologies and practices. Case in point is the electronics industry and information technologies—the Internet boom and impact this had on the overall economic and industrial development. 1990s-era trends include technology taxonomies, manufacturing unit processes, new understanding/definition of national critical technologies, industrial ecosystems, manufacturing foundations, new definitions of competitiveness, corporate merger strategies, outsourced/contracted R&D, and off-shore workforce tactics.

Making Things Better: Competing in Manufacturing, OTA 1990. The report prepared by the Office of Technology Assessment of the U.S. Congress was written in part because of concern about U.S. manufacturing competitiveness with Japan and Germany. Manufacturers in Japan and Germany were able to furnish goods with better performance reliability and ability to control costs. The report (OTA, 1990) identified systematic disadvantages of U.S. manufacturers compared to their Japanese counterparts: (1) lack of coherent government-industry-research institute efforts to foster industry-specific strategic programs promoting technology transfer and development, (2) lack of collaboration between suppliers and customers and in firm-to-firm relationships, (3) unwillingness to share information and technology, (4) reluctance to adapt the newest technological developments from other nations (5) fractured financial support structure, both public and private, (6) weak education and vocational training systems that ultimately diminish worker productivity, (7) disinclination to incur high capital costs to acquire and/or develop new manufacturing technologies, and (8) U.S. antitrust law restrictions.

The report analyzed how the spillover effect of technology transfer may foster a broad range of manufactured products. For instance, advanced television technologies (ATV) such as high definition television (HDTV) were shown to likely impact computer, telecommunication, and other electronics industries.

The following policy efforts were recommended to improve manufacturing: (1) lower capital costs and relieve other pressures in the financial markets, (2) upgrade education and training of manufacturing workers, managers, and engineers, (3) actively engage the U.S. government in technology diffusion throughout the manufacturing sector via technology extension services and subsidized equipment leasing systems, and (4) support R&D for commercially important, not just defense related, technologies that are too costly for individual firms to develop.

The Competitive Edge, Research Priorities for U.S. Manufacturing, 1991. In 1991, the Committee on Analysis of Research Directions and Needs in U.S. Manufacturing started off a series of publications of the National Academy Press about U.S. manufacturing. The *Competitive Edge* (1991) focused on advanced manufacturing technology to promote higher quality, greater responsiveness to consumer demands, and greater capital investment flexibility. The report identified three major technological advances for the future: (1) integration of information and materials handling and processing, which are separate in traditional automation, (2) reliance on higher levels of human and machine intelligence rather than on the skill of operators, and (3) placement of the production process largely under the control of computer programs. The report indicated that successful development of these technologies called for: intelligent manufacturing control, improved equipment reliability and maintenance practices, wide usage of advanced engineering materials, employment of product realization techniques, and focus on manufacturing skills improvements.

The *Competitive Edge* projected that the manufacturing workforce would decline by 20% between 1950 and 2000. A new smaller, yet highly educated workforce was viewed as a necessary precondition for a successful take-off of advanced technologies in manufacturing. In addition, management's ability to quickly restructure operations and adopt "flatter" corporate structures was viewed to be critical.

Future Composites Manufacturing Technology, 1994. In 1994 Japanese Technology Evaluation Center (JTEC) published a report (JTEC, 1994) that makes predictions about polymer composites likely to be utilized by U.S. and Japanese aerospace manufacturers in the future. The report states that the rate of expansion and development of composites technologies stemmed from application of new material technologies to U.S. military and aerospace research projects. After successive oil shocks in the 1970's, the demand for the material was peak high in the early 1980's when U.S. military aircraft pronounced their need for "lighter weight, less fuel." By the 1990's, the advanced composites technologies industry realized its potential in commercial transport and other commercial applications.

The following composites technologies and techniques were expected to be widely adopted in the near future: stitched/RTM; filament winding; pultrusion; continuous sandwich panel; 3-D weaving; mechatronics; automatic tape lay-up machine; automatic ply cutting machine; tow placement; co-curing technology; forming, stamping, injection molding, rolling; repair technology; and material technology. The report took the view that major breakthroughs in usage of composites had already happened, in part because the technologies would not be sufficiently cost-effective to be widely used.

Marshaling Technology for Development, 1994. Marshaling Technology for Development is a collection of publications that were presented at a symposium on technology

and economic development held by the National Research Council and the World Bank. The report (OIANRC and Word Bank, 1994) noted that all areas of an economy, but particularly electronics, were highly dependent on the state of technology. Marshaling Technology expressed expectations for electronics growth associated with developments in silicon, protonics, fast software development, and integrated circuit technologies. These were integral parts of what was termed as “multimedia communication revolution” and creation of a “national information superhighway”. Marshaling Technology noted that because life-cycles for electronics were measured in months (vs. years), electronics companies had to move to integrate formerly separate design, manufacturing, and marketing operations so that manufacturing and marketing specialists were involved at the initial stages of design. CAD (computer-aided design) therefore became a main tool for designing-for-manufacture processes. Advances in million per second instruction (MIPS) technology reduced costs that made computer integrated manufacturing (CIM) more widely used in the electronics industry. Successful application of CAD and CIM in electronics was expected to spill over to other industries.

It was also believed that biotechnology would be a cutting edge research area for manufacturing. Near-term biotechnology related advances included biomedical applications, agriculture, marine biotechnology, animal husbandry, environmental biotechnology, and energy production. However, many biotechnology applications were believed to be too futuristic for near-term commercial exploitation, including biosensors, bioelectronics, biomaterials, biocomputing, and molecular machines and submicroscopic molecules.

National Critical Technologies, 1991, 1993, 1995, 1998. 1990 Defense Appropriations Act established a requirement for creating and maintaining a *National Critical Technologies* (NCT) report. Critical technologies were termed as such because they were advanced, essential for national security, useful for important products and applications, and likely to impact many product applications. The first list of critical technologies was published in 1991, with subsequent reports in 1993, 1995, and 1998. The lists were developed through consensus-based approaches involving panels of experts. The 1995 NCT list divided manufacturing into three areas: discrete product manufacturing, continuous materials processing, and micro/nano fabrication and machining (Table 3). In total, the three areas list 48 specific technologies with 14 of them listed in the micro/nano technology area.

Popper et al (1998) provided a more explicit discussion of the evaluation of the NCTs. In its executive summary, the report identified the following technologies that were viewed as critical by the industry experts: technologies with cross-sectoral ubiquity: software, microelectronics and telecommunications technologies, advanced manufacturing technologies, materials, sensor and imaging technologies; technologies at the interstices: separation technologies, overhaul-and-repair technology, complex-product system-coordination technology; and technologies for society (Popper et al, 1998).

Table 3. National Critical Technologies List for Manufacturing: 1995.

Technology Area	Technology Sub-Area	Specific Technologies
Discrete product manufacturing	CIM support software	Computer-aided design
		Computer-aided engineering
		Process, machine performance database
	Equipment interoperability	Group technology
		Computer-aided process Planning
		Data-driven management info systems
		Factory scheduling tools
		Sensors
		Next generation controller
	Intelligent processing equipment Robotics Auto. Systems for facilities operations Net shape processing	Computer-aided production cycle management
		Building automation systems
		Hot isostatic pressing
Continuous materials processing	Rapid solidification processing	Metal injection molding
		Superplastic forming
		Liquid transfer molding of polymer matrix composites
	Catalysts	Spray forming
		Gas atomization
		Tailored protein catalysts
	Surface treatments	Shape selective catalysts
		Catalysts by design
		Biometric catalysts
	Ultrapure refining methods	Laser hardening
		Thin films
		Grinding and machining of ceramics
Micro/Nano fabrication and machining	Pollution avoidance	Ceramic coatings
		Various refining methods
		Electron beam processing
	Predictive process control	Process design strategies
		Improved processes
		Design for the environment
	Semiconductor manufacturing technology	Industrial ecology
		Sensors
		Data processing
	Semiconductor integration technologies Artificial structuring methods	Silicon machining
		X-ray lithography
		Microwave plasma processing
	Semiconductor manufacturing technology	Electron/ion micro-beams
		Artificially structured materials
		Laser-assisted processing
	Semiconductor integration technologies	Metrology
		Design testing
		Integrated packaging
	Artificial structuring methods	Multichip modules
		Chemical vapor and sputter deposition
		Molecular and chemical beam epitaxy
		Spin-on deposition
		Vacuum evaporation

Source: National Critical Technologies Report (1995).

Unit Manufacturing Processes, 1995. This report (UMPRC, 1995) focused on distinguishing various types of manufacturing processes and the specific technologies necessary to achieving further process efficiencies. Manufacturing processes were grouped into mass-change processes, phase-change processes, structure-change processes, deformation processes, consolidation processes, and integrated processes. The report committee agreed on six enabling technologies that were central to the various manufacturing processes: material behavior, simulation and modeling, sensor devices, process controls, process-related precision and measurement technology, and process equipment design. Research opportunities were identified in each of these technological areas. For example, the following material behavior research opportunities were identified: quantification of the material microstructure, systematic representation of the relationship between the microstructural features, process maps of defect and damage criteria, characterization of boundary conditions, and materials property databases.

Next Generation Manufacturing, NSF 1995. NSF was the lead sponsor of the Next Generation Manufacturing (NGM) project in 1995. NGM was designed to put forth a vision of the future of manufacturing. More than 5,000 experts worked with a project team to produce the final report (NSF, 1995).

A next generation manufacturing company was defined as an “extended enterprise with multiple and ever-shifting business partners” (p.53). The definition explicitly emphasized the shift from a concept/notion of a profit-making unit to a broadly networked/systemic unit extending from “the supplier’s supplier to the customer’s customer.” Next generation manufacturing therefore promoted a future shift in business practices from lean manufacturing to agile manufacturing, defined as a “loose confederation of affiliates that form[ed] and reform[ed] relationships depending on changing customer needs” (p.56). In addition, the report predicted that narrow computer-controlled machine tools would be replaced with rapid prototyping and free form fabrication. Eventually, the report predicted, the line separating manufacturing and service industries would become increasingly blurred, resulting in new definitions of industrial activities.

Visionary Manufacturing Challenges for 2020, 1998. In 1998 the National Research Council's Board on Manufacturing and Engineering Design established the Committee on Visionary Manufacturing Challenges. The Committee set 2020 as their benchmark to enable revolutionary, as opposed to evolutionary, thinking about manufacturing. Conclusions were based on the results of a workshop of academic researchers in manufacturing-related disciplines and a survey of industry experts (CVMC, 1998).

The competitive environment in which manufacturing would operate in 2020 was envisioned to require rapid response to changing market forces, greater product customization, competition based more on innovation and creativity, decreasing the dimensional scale of innovation manufacturing processes and products, greater emphasis on environmental protection through near zero waste, instantaneous conversion of information into relevant knowledge for decision making, and greater globalization of production resources.

The following ten technology spheres were chosen as the most critical directions, in which substantive and timely research was needed:

- adaptable, integrated equipment, processes, and systems that could be readily reconfigured;
- manufacturing processes that minimized waste production and energy consumption;
- innovative processes to design and manufacture new materials and components;
- biotechnology for manufacturing;
- system synthesis, modeling, and simulation for all manufacturing operations;
- technologies that could convert information into knowledge for effective decision making;
- product and process design methods that addressed a broad range of product requirements;
- enhanced human-machine interfaces;
- educational and training methods that would enable the rapid assimilation of knowledge; and
- software for intelligent systems for collaboration.

The report put special emphasis on biotechnology for manufacturing and its potential for developing revolutionary products and processes. Further research was recommended to better understand the precision and flexibility of biological processes. Particular areas of interest included biomemory and logic devices that could recognize, learn, and adapt; biomaterials such as durable ultrasoft membrane materials and materials based on genetically engineered biological feedstocks; fabrication of parts and assemblies with design enzymes, tissues, and biocatalysts; and self-organizing manufacturing systems. It was believed that self-organizing manufacturing systems could leverage bioprocessing technology to develop new approaches for deploying manufacturing equipment, tools, human capital, and software.

Also important to manufacturing in the future were technologies that enhanced large and small scale manufacturing simulations using real-time control at all levels of manufacturing, multi-purpose network technologies, and effective combination of human and computer interaction for efficient, real-time decision-making.

The New Decade of the 21st Century (2000s)

Concerns about low-cost competition drove technological forecasts in the early 2000s to emphasize the adoption of high value, innovative manufacturing approaches. Emphasis was placed on new product development technologies such as modeling and simulation, the use of technology for sustainable manufacturing, and knowledge management practices to ensure effective supply chain integration. Predictions called for the integration of manufacturing

process techniques with biomaterials and micro- and nanotechnology to produce the next wave of high value products and production technologies.

Integrated Manufacturing Technology Roadmap, 2000. The Integrated Manufacturing Technology Roadmap Initiative (IMTI, 2000) is a nonprofit organization set up to help direct future manufacturing investments. The U.S. Departments of Commerce, Energy, Defense and the National Science Foundation sponsor IMTI, and there are many leading company members as well. IMTI's initial roadmapping exercises culminated in a report in 2000. Since that time, other projects and reports have followed to further embellish the roadmap.

The 2000 roadmapping began from the assumption that "all enterprise systems and processes interconnect[ed] seamlessly and dr[ew] on a deep base of science capturing experience to enable design, manufacture, and support of products with unprecedented speed, accuracy, and cost-effectiveness" (p.10). It was also assumed that competitive advantage came from innovation and creativity. Five roadmaps comprised the effort: (1) information systems, (2) modeling and simulation, (3) manufacturing process and equipment, (4) technologies for enterprise integration, and (5) intelligent controls. These roadmaps were designed to address six "grand challenges" for a modern enterprise: lean, efficient production; customer-responsiveness; total connectedness; environmental sustainability; knowledge management; and technology exploitation.

The report acknowledged that lean manufacturing principles have been widely adopted. However, eliminating industrial wastes posed some difficulties, in particular, it was said to contribute to relative losses in operational flexibility and lowered improvement potential. IMTI suggested that manufacturers achieve higher levels of improvement by incorporating into lean processes such technologies as newly engineered materials, micro-electromechanical systems (MEMS), nanodevices, biological processing, and freeform fabrication techniques. IMTI also suggested increased utilization of unobtrusive networks of low-cost sensors in manufacturing control systems.

According to the report, customer responsiveness will rest less on quality and advertising and more on customer relationships, customer satisfaction, and soliciting ideas for products and services in the future. Totally connected enterprises will move beyond enterprise resource planning (ERP) and product data management (PDM) systems to link internal functions and external partners. As manufacturers increasingly depend on their suppliers, supply chain management (SCM) will connect processes and equipment with a web of suppliers and partners to enable critical data sharing and dynamic business relationships.

Environmental sustainability will become a basic cost of doing business. This means that manufacturers will have to move beyond process technology to compete with other countries with lax environmental regulations. It is predicted that greater emphasis will be placed on zero net lifecycle approaches, products engineered at the molecular level to replace environmentally undesirable materials, and products with longer lives that can be recycled or reused.

Greater demand will exist for knowledge management that only involves not just analysis of basic data but also experience and lessons learned. Knowledge mapping, process prototyping, electronic collaboration, and knowledge management teams are among the knowledge management techniques coming to the forefront.

Emerging process and product technologies will continue to drive economic development. These include micro-electromechanical systems (MEMS), rapid prototyping, freeform manufacturing, net-shape and fixtureless processes, ultra high-speed machining,

intelligent assembly, flexible material handling, and remanufacturing technologies that will enable totally closed-loop product life cycles. Receiving sufficient resources to enable rapid development and exploitation is the key in ensuring that technology enables manufacturers to provide customers with high quality, cost-competitive products.

Surviving Supply Chain Integration, 2000. At the request of the National Institute of Standards and Technology and U.S. Senator Robert Byrd, the National Research Council (NRC) formed a committee to study the challenges that integrated supply chains pose to small and medium sized manufacturing establishments (SMEs) (CETS, 2000). Integrated supply chains, in which customers and suppliers work together to optimize their performance, were expected to be more prevalent in the future. Integrated supply chains rely on just-in-time low inventory systems, suggesting that quality components from suppliers are even more critical. The rate of implementation of techniques such as six sigma, ISO certification, and statistical process control therefore is expected to increase. To further reduce redundant inventories and excess manufacturing capacities, manufacturing enterprises will invest more in supply chain communication system, flexible manufacturing techniques, and sophisticated logistics systems.

The report recommended that SMEs find ways to provide value-added services, such as storage, rapid response to warranty issues, ready access to spare parts, improved logistics, and increased design capabilities. In response to increasing customer expectations for timely service and support, SMEs should make effective use of Internet and Web technologies to release announcement, post maintenance manuals, get customer's response, answer questions, and place orders. Senior management in these enterprises should monitor changes in information technology, invest in basic capabilities and plan for future investments. In addition, management should have a strategic view of the business environment rather than focusing on daily business issues alone. Due to the limitations of resources, SMEs should develop partnerships to achieve competitive advantage at lower cost and improve their responses to changing business conditions.

Information Systems and the Environment, 2001. This report is based on a National Academy of Engineering-sponsored workshop that explored how information technology could be used in the future to support sustainable manufacturing. Monsanto's CEO, Robert Shapiro, predicted that "the early twenty-first century is going to see a struggle between information technology and biotechnology on the one hand and environmental degradation on the other. Information technology is going to be our most powerful tool...The substitution of information for stuff is essential to sustainability" (Allenby, 2001). For example, textual material, data, and software upgrades provided through the Internet and via electronic mail can substitute for physical products. The ability for this substitution depends on continued reductions in the cost of information processing and exchange that result from the rate of technological evolution in chip capacity and memory, optical transmission, information storage, signal compression, and efficient spectrum use.

Deanna Richards and Michael Kabjian (2001) proposed that knowledge management techniques can enhance the use of information technology in sustainable manufacturing in relationships with upstream suppliers, downstream customers, and collaborations with other firms, government, and academia. Knowledge management technologies encompass data management; document management systems; groupware and collaborative applications; networking, intranets, extranets, and the Internet; and information retrieval. Knowledge

management faces many challenges in the current business environment such as corporate outsourcing and contracting, rapid employee turnover, downsizing, and telecommuting-enabled disbursement of workers across the globe.

Several product design and development techniques were proposed to incorporate sustainability directly into new products. Thomas Graedel (2001) recommended the use of environmental information in “gate reviews” at each stage in the product realization process. Kosuke Ishii (2001) proposed integrating recyclability into modular design through methods such as quality function deployment and design for assembly tools. Reverse fish-bone diagrams can represent a product’s retirement process and recyclability maps can provide information on materials and assembly to improve recyclability.

Attention must also be paid to consumption of energy, which is anticipated to increase rapidly, particularly in Asia (Ishii, 2001). Energy use is likely to be more expensive in the future, it is likely to shift from primary fuels to electricity, and new energy infrastructure will have to be built to accommodate these trends.

Modeling and Simulation in Manufacturing and Defense Acquisition, 2002. This is a report of the National Research Council’s (NRC) Committee on Modeling and Simulation Enhancements for 21st Century Manufacturing and Acquisition, which was formed in response to a request by the U.S. Department of Defense (DOD). Modeling and simulation (M&S) are important to DOD decisions about future combat situations that minimize risk and to commercial manufacturers’ efforts that “quickly innovate, design, and produce the ‘right product right’ the first time” (BMED, 2002).

M&S has been applied to the lifecycle of a system-of-systems rather than to a single component. To maximize the effectiveness of M&S, basic research needs to be conducted in areas such as scalability and object oriented technology, multiresolution modeling between various resolution levels during run times, agent-based modeling that adequately represents behavior, semantic consistency between different simulation systems, abstract modeling to represent situations under conditions of minimal knowledge and time, fundamental limits of modeling and computation, and models evaluating uncertainty and risk in dangerous situation. Also important to M&S application is development of shared process, database, standards, and architecture infrastructures.

The NRC report (1999; cited in BMED, 2002) specified four priorities for R&D of defense manufacturing for the year 2010 and later: (1) efficient sustainability of weapons systems; (2) modeling and simulation based design tools; (3) leveraging of commercial resources; and (4) crosscutting defense-unique production processes. M&S can address these areas by promoting the development of models of defense products, manufacturing processes, and life-cycle performances; developing algorithms for design trade-offs that optimize life-cycle costs; developing enhanced and easily usable parametric models that facilitate design trade-offs at the conceptual stage; and initiating the development of product database that will permit simulation at various levels of resolution.

1.4 Conclusions

Over the last fifty years, there has been significant change and evolution in the U.S. manufacturing base and in how, at any particular point in time, it forecasts technological prospects and trajectories. A noticeable theme in these forecasts is the increased coupling, over time, of assessments of technological paths and opportunities with assessments of broader

economic, social, and competitive trends. Thus, in the immediate post-World War II decades, forecasts emphasized continued improvements to mass production such as standardization, functional specialization, coordination and planning, and how to integrate workers into automated processes. Such forecasts predicted a “technologically-determined” path, with implicit assumptions of American manufacturing preeminence, and less attention to human factors. By the 1980s, competition with Japan and Germany had resulted in dramatically changed business practice predictions. The rise of the Toyota method, flexible production, mass customization, inter-company teams and investments, and empowered workers were evident in 1980s- and 1990s-era business practice literature. Studies of this era emphasized the importance of the internal relationships between workers, managers, and technology and of the linkages between suppliers and customers in supply chains. Today, there is a new emphasis on viewing technological change in the context of knowledge and intellectual capital. Recent studies have highlighted calls for innovation-based business strategies supported by knowledge management systems, rapid product development, and decreased dimensional production scales. Significantly, technologically progressive companies are viewed in the context of a *network* of knowledge-based and innovation relationships and clusters.

In contrast with the relatively upbeat tone of technological and business practice estimates, global competition has been a consistent concern since the rise of globalization and multinationals in the 1970s. It was in the 1970s that fears about routine competition from low-wage, less developed countries increasingly surfaced. In the 1980s, concerns expanded to focus on high-end competitor countries, Japan and Germany and, in the 1990s, fast developing yet technologically capable “tigers” such as Korea and Taiwan. Yet, also in the 1990s and continuing into the 2000s, U.S. manufacturers’ global concerns shifted again, this time to focus on China which, today, has a huge reservoir of low-cost labor, but is increasingly upgrading its technological capabilities.

Forecasts about the manufacturing workforce also have reflected worries. For example, there has been an ongoing tension between technological and business practice advances and the numbers and types of jobs available in the manufacturing sector. Fears that automation and industrial management developments will simplify manufacturing tasks and utilize machinery or computers instead of workers have been expressed since the 1950s. The debate about the nature of manufacturing work and employment has been juxtaposed against the rise of the post-industrial society and the growth of the service and/or information economy.

At root, however, this brief historical review of studies of the future of manufacturing technology has shown an enduring belief in the future itself – in the concept that, despite current challenges and difficulties, the U.S. innovation system is capable of developing and adopting new technologies and techniques that promise to sustain the manufacturing base. In practice, technological forecasts tend to deliver less than promised, although in every technological generation there are always surprising outcomes. Lags in the take-up of predicted technologies are, perhaps, partly a reflection of the perpetual over-optimism of technology proponents. Market failures and path dependencies (including the sunk costs, institutional rigidities, and network effects associated with older technologies) are also part of the story. At the same time, there are arguably also issues related to implementation systems for new technology in the U.S. (including corporate time horizons, financial systems, training, and policy) that affect adoption. These are all discussions for another paper, not this one. But, as we enter a new round of assessment of future technologies that can sustain U.S. manufacturing in the face of international competition – involving possibly manufacturing at nano-scales, the fusion of bio and

engineering, and further transformations of what manufacturing is and can do – it is always worthwhile to keep these contextual elements and challenges in mind.

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Table A.1. Technologies and Economic Environment, U.S. Manufacturing, 1950-2000.

Decade	Domestic and Global Economic Environment	Leading-Edge of Current Technologies	Future Technology “Predictions”	Trends in Management Practices	Workforce Impact, Concerns
1950's	Rise of post-industrial society; Mass market expansion and stable economic growth in manufacturing	Mass-production; assembly line; dedicated tools Emergence of real-time processing – but with high cost	Automation; Digital computation; Linear programming; Advances in inventory control; quality control; statistical quality control	Concern about flexibility; The problem of the black-box approach in factory production control	Early fears about automation and workerless factories; First discussion of computerization; Concern about the situation of small units in automation era; The shortage of engineer and programmer
1960's	MNC's shifting to low-wage companies; Growing economy; The increase of the geographical mobility of industry; Expansion and diversification of enterprises	Greater emphasis on the use of gasses, liquids, electric power, and pure compounds and lesser emphasis on natural products, crude mixtures, and solids	Automatic language translation; Moore's law	Idea of product life cycles; Split routine manufacturing from R&D	Concern about loss of shop-floor jobs; confidence about retention of R&D, management, and advanced production jobs
1970's	Continued globalization; Declining economy; Slower rate of growth for manufacturing; The creation of new science-based industries; Geographical expansion; Environmental regulations effecting traditional industries	NC Tools; Microprocessor; Microelectronics; Multiple processor on chip; Computer control 'boom'	CAD	Realize the limit of vertical integration; The obsolete of conventional batch manufacture; Shrinking manufacturing cycle; Reduce inventory; Slash delivery times; Radical revision in management structures	Renewed debate; Fear of loss of jobs; “Deskilling”; Problem of overcapacity; Concern of greater government control over technology

Table A.1. Technologies and Economic Environment, U.S. Manufacturing, 1950-2000.

Decade	Domestic and Global Economic Environment	Leading-Edge of Current Technologies	Future Technology “Predictions”	Trends in Management Practices	Workforce Impact, Concerns
1980's	Intense globalization; Growing economy; Increasing speed of changes in the overall economic environment	CIM; CNC, EDM; CAD; Robotics; Control systems (Computer control, robotics); AGV; Automatic recognition systems; MAP; New materials: polymer, ceramics; FMS	Further: MAP AGV; Completely ceramic motor engine; Combination of smart robots and flexible fixturing, FMS; wide application of AI expert systems; Needs: Automatic storage and retrieval of individual items; flexible fixturing; uniform robot programming language; Predictive information technologies	Quality controls; Toyota method; Inventory management; Just-in-time production; Integration of production functions	High wage competition (Japan, Germany); Better production management practices; Lower costs due to shorter product life cycles, wide application of JIT, FMS in Germany and Japan
1990's	Intense globalization and regionalization; EU economic integration; Rise of trading blocks; Rise of Asian Tigers followed by Asian Crisis, Japanese economic recession; Productivity gains in the US; Recovery of manufacturing; Industrial concentration/selected industries; Industrial ecology; Fast advanced in Information	Focus on commercially-important technologies; HDTV, flat panel liquid crystal display; Digital technologies; Fiber optics; Silicon and integrated circuit technologies, protonics, software development, MIPS (million instructions per second); Critical technologies; Intelligent manufacturing control (IMC); Internet boom;	Digital technologies; Biotechnology (biomemory, biologic, membrane materials); Global production networks; Self-organizing manufacturing systems; Genetic engineering; Built-in self-test; Chip-on-glass	Lean manufacturing; Time-to-Market; Flatter organizational hierarchies; Greater responsibility of floor managers and empowered employees; Greater number of domestic and international Joint Ventures for cost-sharing and access to new markets; Corporate mergers and acquisitions, corporate restructuring	Moore's law, Renewed debate; Cross training/ Smaller workforce with multidisciplinary highly technical skills; Cheap foreign labor gains

Table A.1. Technologies and Economic Environment, U.S. Manufacturing, 1950-2000.

Decade	Domestic and Global Economic Environment	Leading-Edge of Current Technologies	Future Technology “Predictions”	Trends in Management Practices	Workforce Impact, Concerns
	Technology; Intersectoral flow of technologies	Nanotechnology, new materials (manipulate molecules); Life sciences			
2000’s	Declining economy; Mature E-commerce	Rapid prototyping; Freeform manufacturing; Net-shape and fixtureless processes; Ultra high-speed machining; Intelligent assembly; Flexible material handling; Remanufacturing technologies; Modeling and simulation; InfoSleuth™	Use of nanotech and living molecules to make wires, biomaterials; Microelectromechanical systems (MEMS); Nanodevices; Biological processing; Freeform fabrication techniques; The provision of textual material through internet; Groupware	Innovation and creativity being the competitive advantage; Knowledge management; Intelligent, on-line advisor; Customer/requirements driven manufacturing; Lifelong relationship with customer; Zero net life-cycle waste	On-demand training

2

Technological Opportunities to Develop New Capabilities: Manufacturing, Strategic Engineering, Adaptive Technologies, and Controls

Session Chair: Philip Shapira (SPP)

2.1

Manufacturing Directions from Manufacturing Research Center (MARC) Perspective

Steven Danyluk¹

The manufacturing systems of today have been changing along the three main directions. The first direction involves a shift from mass production to semi-customized products. Full customization is not feasible due to diverse customer demands. The second change is from complete in-house production to a more collaborative, multi-participant venture, which enables companies to increase speed of product development, reduce overall business risk, and better penetrate local markets. The third is that the former staple of centralized control of manufacturing facilities has been transformed into a system of coordination of distributed manufacturing sites, which in turn, has increased productivity, simultaneously creating wealth for the nation.

The manufacturing community has responded to these changes in two main ways: (1) by creating intelligent manufacturing systems, and (2) by researching areas of molecular manufacturing. Within intelligent manufacturing systems, researchers are focused on product life cycle management, models of intellectual capital, management of IT advances in engineering knowledge representation, process development for clean, efficient, flexible, and sustainable operations, various strategy, planning, and design tools such as re-engineering, and the overall enterprise operations such as logistics, business process modeling, and enterprise resource planning (ERP).

Molecular manufacturing includes more than nanotechnology. It covers any manufacturing process that uses single molecules to create computer circuits on a chip with greater density. This particular direction of research yields great potential over the next 50 years.

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responsible. The three features are directly related to the availability of resources, redesign, and remanufacturing of products as well as business practices and social equity.

Finally, 9-11 raised two issues previously unaccounted for in designing distributed manufacturing sites software: (i) security, and (ii) disruption of supply chain. Remote manufacturing issues were always salient where the preferences were given to face-to-face communications, relative locational proximity, and timing.

Incorporating all of the above-specified issues that are faced by today's manufacturing systems, new software tools facilitate the creation of new infrastructure, an entirely new framework for how manufacturing is done (Figure 2.1.2). GT and MARC have been working on creating such an infrastructure focusing on developing all interconnections. Within electronics manufacturing systems, we connect everything up through supply chain and ERP systems. MARC research is focused on one- to two-year time horizons. It is involved with such corporations as MACOM, part of Yazaki, Nortel, Siemens, HP. Working with such multiplicity of companies allows the Center to run simulations at various sites. In practice, Center's products are recognized as the standard software tools used in the distributed-sites manufacturing systems.

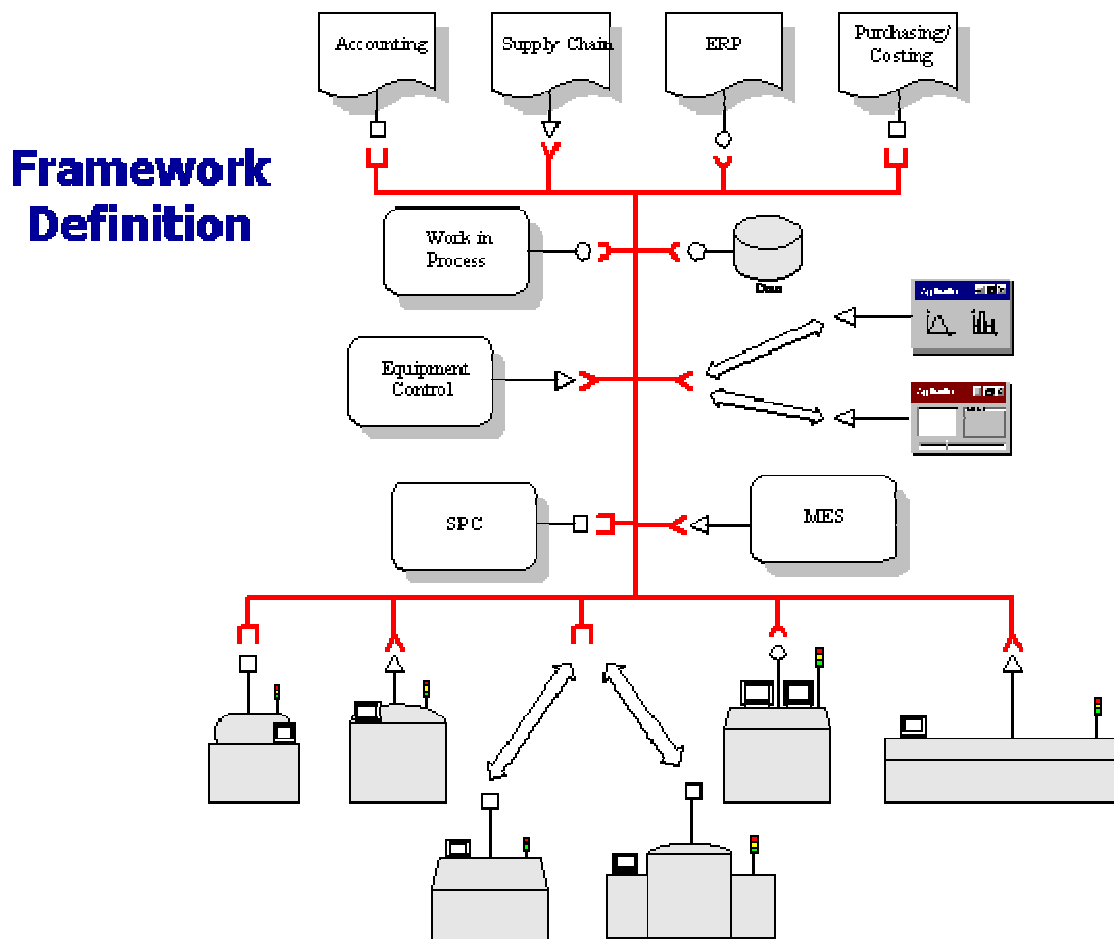


Figure 2.1.2. Framework Definition.

2.2

Strategic Engineering on the Integrated Design of Products and Processes

Farrokh Mistree¹

In most discussions on manufacturing there is this core assumption that we have lost manufacturing in the sense of making/producing things and that most of our manufacturing facilities have centered overseas. The proposition that usually follows this core assumption is that we have to do something. Many propose various ways to retain the building base of manufacturing.

I challenge these pronouncements in a number of ways. First of all, I believe that we should take care of the people who have lost jobs, and the main venue for doing this is through retraining. However, as Georgia Tech researchers we have to think strategically. As such, we have to create an entirely new infrastructure—a new paradigm for education as well as manufacturing, the interaction-integration paradigm. As President Clinton once noted: the ‘globalization genie’ is out of the bottle and it can not put back. We, as strategic developers, need to devise such policies that would account for the ‘genii,’ otherwise, we are risking to face a failure in the long-term.

Throughout the human history we have seen examples of two processes that related to manufacturing: interaction and integration. For instance, prior to the first industrial revolution there were individual craftsmen, who chose to integrate with fellow craftsmen and to form guilds. During the first industrial revolution production is integrated vertically, taking advantage of the existing space availability. This, in turn resulted in mass production, bringing the entire manufacturing world to yet another significant threshold—the Sloan of GM, mass customization. In a way, the challenges that we are facing today were also present in the early part of the last century.

Today, human life and computers are linked inexorably, integrated, and we are moving towards the age of cyborgs. As productive individuals we can not divorce ourselves from the computer technology—we get upset when something happens to our operating systems. Hence, no longer can a computer be seen as a mere tool of interaction. In essence, it has become our integration mechanism.

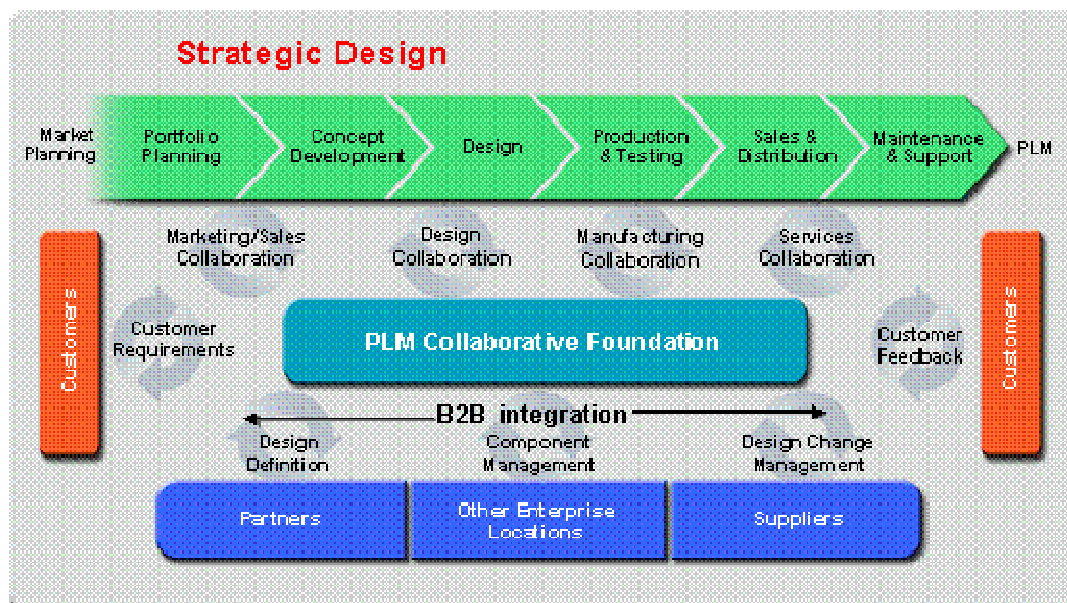
It is important to remember that a cyborg engineer should be visualized all over the world. This is related to the notion that product development and information exchange will be occurring and used throughout the world. There is also a need to remember that our world is, and should be maintained, green. The paradigm enhances the notion that engineering should take into account the environmental and other social purposes from

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the very beginning of the engineering process. Today's web technology moves us further towards such intellectual/inter-disciplinary integration.

Strategic design within product manufacturing lifecycle requires transporting of tremendous amount of information/data from market planning, portfolio planning, etc. to production and distribution stages. Successful implementation of new product life cycle management systems requires, what we call, strategic engineering. Strategic engineering is defined as a comprehensive approach for designing products and processes that efficiently and effectively accommodate both (i) changing markets and associated customer requirements, and (ii) technological innovations in a collaborative, distributed environment while safeguarding the economic viability of a company.

Product Lifecycle Management



Courtesy Stas Tarchalski, IBM Product Lifecycle Management

Figure 2.2.1.

The objectives of strategic engineering are as follows:

- To establish a method for allowing distributed designers to collaborate on the design of products while taking into account “changes in market trends”, “changes in the capabilities of existing technologies” and “new or evolving technologies;”
- To develop a number of new techniques that would be parts of a strategic design method, including “*N-dimensional market visualization techniques*” and “*Innovation modeling and early technology impact forecasting methods*;” and
- To develop a plan for coordinating the many disparate methods that would make up strategic design as well as a logic for choosing between different modes of managing product variety.

Further, the benefits gained by implementing the principles of strategic engineering include:

In relation to academic scholarship:

- Effective tools for creating representations of n-dimensional market spaces and design capabilities;
- Systematic approaches for designing families of products that can evolve and accommodate change and innovation and a systematic tool for choosing between multiple available approaches;
- Methods for forecasting and characterizing the impact of innovation on a feasible space in a manner meaningful to the design process; and

In terms of industry applications:

- Computing, information, and decision frameworks for coordinating distributed decision makers carrying out strategic design; and
- Methods for linking market and design capability forecasts to design decisions and plans for product portfolios.

In addition to offering numerous benefits, strategic engineering requires resources, with the main capital being human. A degree in strategic engineering should encapsulate a specialized engineering degree with a strong component of management and public policy knowledge/skills. With such knowledge asset-base, a strategic engineer becomes an innovator, leader, entrepreneur, and a policy shaper.

2.3

Additive Manufacturing Technologies: Opportunities for Customization, Flexibility, Complexity, and Simplicity

David W. Rosen¹

Additive manufacturing (AM) is the usage of layer-based “rapid prototyping” technologies for production manufacturing. AM stands in contrast to typical manufacturing processes where material is removed (e.g., machining) or formed (e.g., molding, stamping). In general, AM applications have taken advantage of the geometric complexity capabilities of rapid prototyping (RP) technologies to produce parts with customized geometries. As such, AM is not a replacement for mass production applications since the economics of RP technologies do not enable high volume production.

In this paper, a brief introduction to AM processes will be given, three major applications of AM will be presented, from Align Technology, Siemens/Phonak, and On-Demand Manufacturing, then unique characteristics of RP technologies are identified that potentially lead to AM. Some of the potential impacts of AM and some potential deployment scenarios will be offered that could change the roles of traditional consumers and manufacturers.

Additive Manufacturing Technologies

Additive manufacturing is characterized by the addition and processing of materials during manufacture in a freeform manner, without the need for hard tooling. As a result, complex, 3-dimensional parts and devices can be produced without investing time and money into molds, fixtures, masks, or other fixed tooling. One technology, stereolithography (SL), will be presented in some depth and others with compared to it.

Stereolithography

SL machines have been commercially available since the late 1980s. Most commercial SL machines from 3D Systems (www.3dsystems.com), the only SL vendor in the US, have a laser spot size of 0.24 – 0.26 mm diameter. This beam size dictates the minimum feature size capability. One model, the Viper Si2, by 3D Systems, has a smaller beam diameter of about 80 μm .

A schematic of a typical commercial SLA machine is shown in Figure 1. Parts are manufactured by fabricating cross sectional contours, or slices, one on top of another. In commercial SLA machines, these slices are created by tracing 2D contours of a CAD model in a vat of photopolymer resin with a laser. The optics system includes a laser, focusing and adjustment optics, and two galvanometers that change the laser beam's position in the vat. The prototype to be built rests on a platform that is dipped into the vat of resin. After each slice is created, the platform is lowered, the surface of the vat is

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recoated, then the laser starts to trace the next slice of the CAD model, building the prototype from the bottom up. During the part preparation phase, the SL machine user has the opportunity to specify many process variables, including layer thickness, resin parameters, and the amount of inter-layer bonding (overcures = cure depths into the already cured material in the previous layer). A more complete description of the stereolithography process may be found in [1].

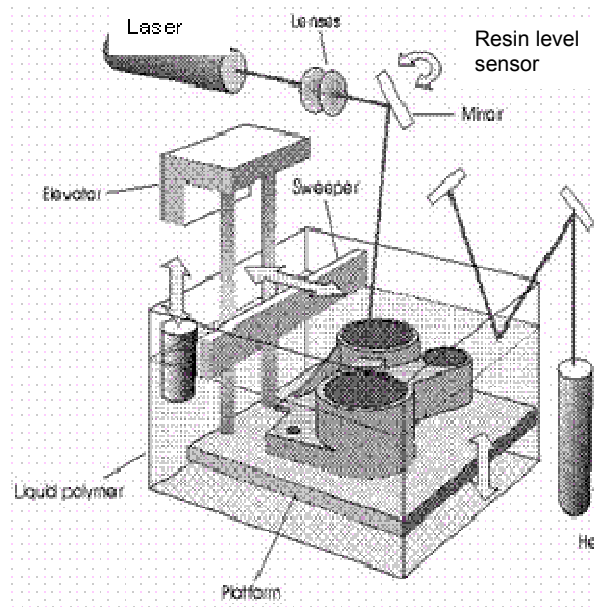


Figure 2.3.1 SL machine and schematic.

Other Technologies

The Selective Laser Sintering (SLS) process is similar to SL, but parts are fabricated in a vat of powder, instead of liquid resin. A CO₂ laser partly melts powder particles so that they fuse (“sinter”) together as the laser scans a part cross-section. 3D Systems, EOS, and several other companies worldwide market SLS machines. Several different polymers and metal materials are available (nylons, steels, aluminum, and titanium alloys). Fused Deposition Modeling (FDM) machines are marketed by Stratasys (US) (www.stratasys.com). In this technology, a filament of polymer is heated and extruded through a narrow nozzle to deposit material.

Production Manufacturing Examples

Align Technology

Align Technology, in Santa Clara, California, is in the business of providing orthodontic treatment devices (www.aligntech.com). Their Invisalign treatments are essentially clear braces, called aligners, that are worn on the teeth. See Figure 2.3.2. Every 1 to 2 weeks, the orthodontic patient receives a new set of aligners that are intended to continue moving their teeth. That is, every 1 to 2 weeks, new aligners that have slightly different shapes are fabricated and shipped to the patient’s orthodontist for fitting. Over the total treatment time (several months to a year typically), the aligners cause the patient’s teeth to move from their initial position to the position desired by the orthodontist. If both the



Figure 2.3.2 Aligner from Align Technology. Courtesy Align Technology

upper and lower teeth must be adjusted for six months, then 26 different aligners are needed for one patient, assuming that aligners are shipped every two weeks.

The need for many different geometries in a short period of time requires a mass customization approach to aligner production. Align's manufacturing process has been extensively engineered. First, the orthodontist takes an impression of the patient's mouth with a typical dental clay. The impression is scanned using a laser digitizer. The resulting point cloud is converted into a tessellation (set of triangles) that describes the geometry of the mouth. This tessellation is separated into individual teeth,

enabling an Align Technology technician to perform treatment operations as prescribed by the patient's orthodontist. Each tooth can be positioned into its desired final position. Then, the motion of each tooth can be divided into a series of treatments (represented by different aligners). After manipulating the geometric information into specific treatments, aligner molds are built in one of Align's 18 SLA-7000 stereolithography (SLA) machines. The aligners themselves are fabricated by thermal forming of a sheet of clear plastic over SL molds in the shape of the patient's teeth.

Between 1999 and 2002, 50,000 patients have been treated using over 2 million aligners. Align's SLA machines are operated 5 days a week for 24 hours per day. Typically 100 aligner molds are fabricated in one build and 60-70 builds per day are produced. To achieve rapid manufacturing, Align needed to invent a new type of manufacturing process, develop specialized equipment for the process, modify software tools and develop information technology for their operations.

Siemens and Phonak

Siemens Hearing Instruments, Inc. (www.siemens-hearing.com) and Phonak Hearing Systems are competitors in the hearing aid business. In the early 2000's, they teamed up to investigate the feasibility of using Selective Laser Sintering (SLS) technology in the production of shells for hearing aids [2]. A typical hearing aid is shown in Figure 2.3.3. The production of hearing aid shells (housings that fit into the ear) has required many manual steps. Each hearing aid must be shaped to fit into an individual's ear. Fitting problems cause up to 1 out of every 4 hearing aids to be returned to the manufacturer, a rate that would be devastating in most other industries.

Traditionally, an impression is taken of a patient's ear, which is then used as a pattern to make a mold for the hearing aid shell. An acrylic material is then injected into the mold to form the shell. Electronics, controls, and a cover plate are added to complete the hearing aid. To ensure proper operation and comfort, hearing aids must fit snugly into the ear and must remain in place when the patient talks and chews (which change the geometry of the ear).

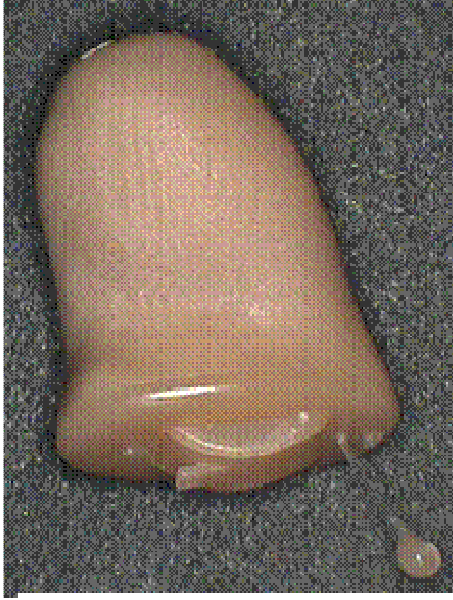


Figure 2.3.3 Siemens LASR ® Hearing Aid and Shell.

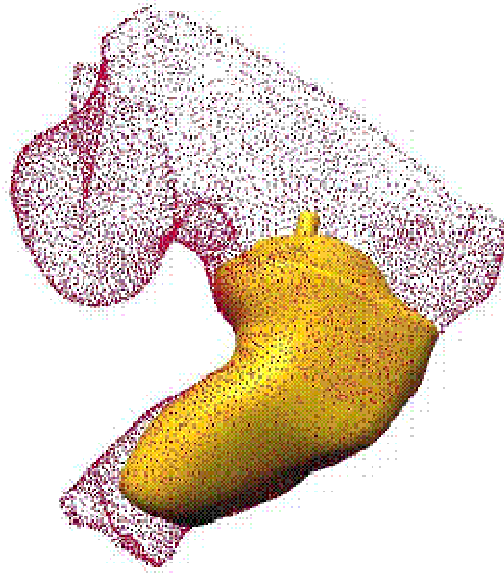


Figure 2.3.4 Hearing Aid within scanned Point Cloud.

To significantly reduce return rates and improve customer satisfaction, Siemens and Phonak sought to redesign their hearing aid production processes. Since RP technologies require a solid CAD model of the design to be produced, the companies had to introduce solid modeling CAD systems into the production process. Impressions are still taken from patients' ears, but are scanned by a laser scanner, rather than used directly as a pattern. The point cloud is converted into a 3D CAD model, which is manipulated to fine-tune the shell design so that a good fit is achieved. This CAD shell model is then exported as an STL file for processing by the SLS machine. A scanned point cloud is shown superimposed on a hearing aid model in Figure 4.

Currently, Siemens Hearing Instruments produces about 250,000 hearing aids annually. As of Fall 2002, they had produced over 40,000 hearing aids with SLS shells. Their return rate has fallen dramatically with their improved design and manufacturing process. Shells are produced on two SLS machines in a Siemens' facility in the Duraform material. A separate operation is performed after shells are fabricated to modify the surface finish and texture.

The hearing aid shell production illustrates how companies can take advantage of the shape complexity capability of RP technologies to economically achieve mass customization.

On-Demand Manufacturing

In August 2002, a new company was spun-off from Boeing, called On-Demand Manufacturing (www.odm.net). They manufacture non-structural aerospace components in low production volumes. Initial applications are for ducts in F-18 fighter aircraft produced in nylon materials using SLS machines. Some duct parts were produced using roto-molding, a manufacturing process typically used for garbage cans, large plastic children's toys, and other applications requiring large, low tolerance parts. In one duct design, an assembly of 10 parts was replaced by a single parts made in SLS. Not only did

the shape complexity capability of SLS benefit the application, an additional benefit occurred by greatly reducing the part count and enabling the company to eliminate an entire assembly line. On the left in Figure 8 is the original duct design; on the right is the single part that replaced the assembly.

AM Unique capabilities

It is useful to generalize from these two examples and explore how the unique capabilities of AM technologies may lead to new production manufacturing applications. The unique capabilities of interest here include:

- Shape complexity: it is possible to build virtually any shape,
- Functional complexity: functional devices (not just piece-parts) can be produced in one build,
- Material complexity: material can be processed one point, or one layer, at a time. To date, only shape complexity has been used to enable RM, but applications taking advantage of the other capabilities are expected.

Shape Complexity

Essentially, the capability to fabricate a layer is unrelated to the layer's shape. For example, the lasers in SLA and SLS processes can reach any point in a part's cross section and process material there. As such, part complexity is virtually unlimited. This is in stark contrast to the limitations imposed by machining or injection molding, two common processes. In machining, tool accessibility is a key limitation that governs part complexity. In injection molding, the need to separate mold pieces and eject parts greatly limits part complexity.

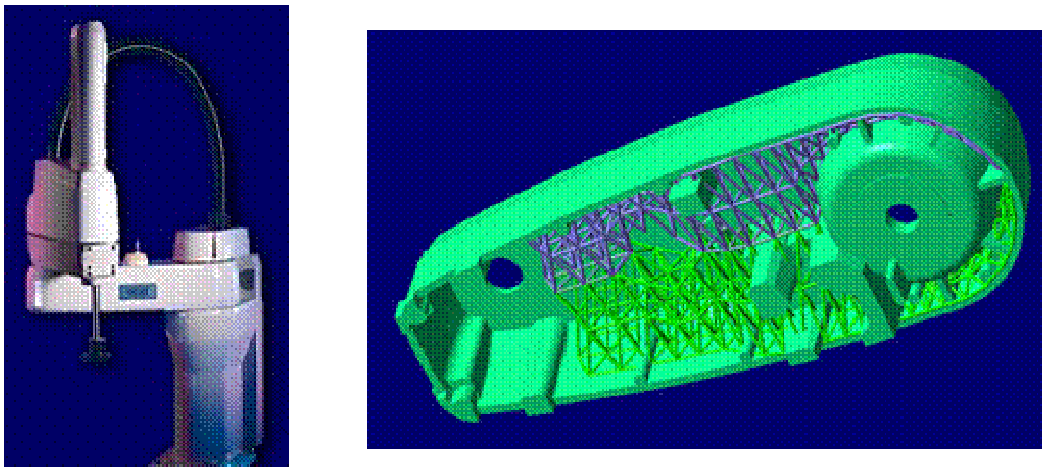


Figure 2.3.5 Robot and a Redesigned Link with Stiffening Truss Structure Added.

A related capability is to enable custom designed geometries, as demonstrated in the examples from Section 2. In production, it does not matter if one part has a different shape than the previously produced part. Furthermore, no hard tooling or fixtures are necessary with RP processes. Hence, lot sizes of one are economically feasible. This is tremendously powerful for medical applications, for example, since everyone's anatomy is different. Also, consider the design of a high speed robot arm. High stiffness and low weight are desired typically. With RP, the capability is enabled to put material where it can be utilized best. The link from a commercial Adept robot shown in Figure 5 has been

stiffened with a custom designed truss structure that conforms to the link's shape. Preliminary calculations show that weight reductions of 25 percent are achieved readily with truss structure and that much greater improvements are possible. More generally, RP processes free designers from being limited to shapes that can be fabricated using conventional manufacturing processes.

Another factor enabling lot sizes of one, and shape complexity, is the capability for automated process planning. Straightforward geometric operations can be performed on STL files (or CAD models) to decompose the part model into operations that an RP machine can perform. Although CNC has improved greatly, many more manual steps remain in process planning and generating machine code.

Functional Complexity

When building parts in an additive manner, one always has access to the inside of the part. Two capabilities are enabled by this. First, by carefully controlling the fabrication of each layer, it is possible to fabricate operational mechanisms in some RP processes. By ensuring that clearances between links are adequate, revolute or translational joints can be created. Second, components can be inserted into parts being built in SLA machines, enabling *in situ* assembly.

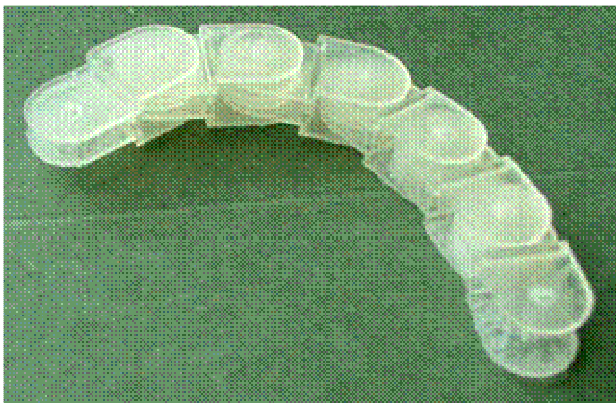


Figure 2.3.6 Pulley-driven snake-like robot.

A wide variety of kinematic joints have been directly fabricated in SLA, FDM, and SLS technologies, including vertical and horizontal prismatic, revolute, cylindrical, spherical, and Hooke joints. Figure 6 shows one example of a pulley-driven, snake-like robot with many revolute joints that was built as assembled in our SLA-3500 machine.

Similar studies have been performed using FDM and SLS. In SLS, loose powder must be removed from the joint

locations in order to enable relative joint motion. In FDM, the usage of WaterWorks support material, which is dissolvable in water, ensures that joints can be movable after post-processing.

In the construction of functional prototypes, it is often advantageous to embed components into parts while building them in SLA machines. This avoids post-fabrication assembly and can greatly reduce the number of separate parts that have to be fabricated and assembled. Furthermore, SLA resins tend to adhere well to embedded components, reducing the need for fasteners.

We have fabricated many devices with a wide range of embedded components, including small metal parts (bolts, nuts, bushing), electric motors, gears, silicon wafers, printed circuit boards, and strip sensors [3, 4]. Shown in Figure 2.3.7 is a model of the elevator in a SLA-250 machine that was built in our SLA-250. It has four embedded components (2 bushings, one lead-screw, and one nut). The platform translates vertically along two shafts, driven by the lead-screw. Device complexity is greatly facilitated when the

capability to fabricate kinematic joints is coupled with embedded inserts since functional mechanisms can be fabricated entirely within the SLA vat, greatly simplifying the prototyping process.

Material Complexity



Figure 2.3.7 SLA-250 Platform Model with 4 Embedded Components.

Since material is processed point-to-point in many of the RP technologies, the opportunity is available to process the material differently at different points, causing different material properties in different regions of the part. Furthermore, some RP technologies enable changing material composition gradually or abruptly during the build process. New applications will emerge to take advantage of these characteristics.

The concept of functionally graded materials, or heterogeneous materials, has received considerable attention, but manufacturing useful parts from these materials often has been problematic. Consider a turbine blade for a jet engine. The outside of the blade must be resistant to high temperatures and very stiff to prevent the blade from elongating significantly during operation. The blade root must be ductile and have high fatigue life. Blade interiors must have high heat conductivity so that blades can be cooled. This is an example of a part with complex shape that requires different material properties in different regions. No single material is ideal for this range of properties. Hence, if it was possible to fabricate complex parts with varying material composition and properties, turbine blades and similar parts could benefit tremendously.

Most direct metal technologies, such as the Optomec (LENS) (www.optomec.com) and POM Group (DMD) machines, have demonstrated some capability for fabricating graded material compositions, so work in this direction is promising.

Future of additive Manufacturing

There is no question that we will see increasing utilization of RP technologies in production manufacturing. In the near-term, it is likely that new applications will continue to take advantage of the shape complexity capabilities for economical low

production volume manufacturing. Longer time-frames will see emergence of applications that take advantage of functional complexity capabilities (e.g., mechanisms, embedded components) and material complexities.

Leading Organizations

World-wide, approximately 35-40 companies offer RP and AM machines. Most are fairly small companies and many operate only in overseas markets. In the US, 3D Systems has been the leader in the development of the commercial rapid prototyping industry. They are also the leader in advancing the concepts of production manufacturing using AM technologies.

Search, development, and technology transfer. Germany's Fraunhofer Institutes are a good example. Five or six Fraunhofers have substantial RP/AM R&D programs. In the Netherlands, TNO has a very large program in advanced manufacturing technologies. Sandia National Labs has the most prominent research program in the US.

Many countries have a significant amount of research underway in universities. I participated in a survey of European AM research sites in October, 2003 that visited 14 sites in the UK, Germany, The Netherlands, Sweden, and Finland. The leading European sites have better equipment, facilities, and funding in the AM area than in the US. These sites include the University of Manchester, Loughborough University, the University of Liverpool (UK), the University of Freiburg (Germany), and the Helsinki University of Technology (Finland).

In Asia, China has by far the largest programs in AM technologies. Tsinghua University in Beijing and Huazhong University of Science and Technology (Wuhan) have the most prominent programs. Many other universities also have research programs. In Singapore, both NUS and NTU have significant research programs, although NTU's tend to be more specialized in narrow application areas. South Korea has research programs at universities (Seoul National, KAIST) as well as within government labs (KIST). Japan's research programs tend to focus on micro-systems and nanotechnology, and less on macro-scale AM technologies.

In the US, the most prominent research programs are at the University of Texas, Austin, the University of Michigan, and MIT. Many other universities have smaller research programs, including Georgia Tech.

Application Areas

One needs only consider the array of devices and products that are customized for our bodies to see more opportunities that are similar to aligners and hearing aids. From eye glasses and other lenses to dentures and other dental restorations, to joint replacements, the need for complex, customized geometries and complex material compositions is widespread in medical and health related areas.

Customized geometry and functionality enable customers to design their own personal communication/computing devices (e.g., future cell phones and PDA's). Structural components will have embedded sensors that detect fatigue and material degradation, warning of possible failures before they occur. The emergence of "smart textiles" and their usage in clothing enables many new applications that will involve electronics, communications, and other technologies. This opens up possibilities for customization

and personalization of entirely new types of products. Additive manufacturing technologies will be needed to fabricate them.

Distributed Manufacturing

As AM technologies improve, the number of machines will increase and their costs will decrease. Since AM technologies are capable of fabricating complex shapes and potentially highly functional devices, it becomes possible to embody an entire manufacturing system within a single, small machine. AM systems will be very flexible in that they will be capable of fabricating a wide variety of parts and, potentially, products or modules. Home AM machines are likely to emerge in under 10 years.

When additive manufacturing systems become available in small, affordable packages, the large centralized manufacturing facilities that predominate now will no longer be necessary. Rather than have manufacturing centralized in low-cost geographic regions, with the associated shipping expenses and time delays, manufacturing sites can be local to cities or even neighborhoods. Imagine how a trip to Home Depot may change. Instead of browsing through a limited selection of kitchen faucets, you specify what you want and, while you continue to shop, the AM machines in that store make your order. Or, you may complete your shopping through their web-site and never have to leave your home.

Going further, you may own an AM system, enabling you to fabricate your own custom designed home fixtures, etc. Trips to Home Depot will be for raw materials, including for your AM system, lumber, and landscaping supplies. Despite their advanced capabilities and flexibility in fabricating devices, future AM systems will be simple to operate. The ink-jet and laser printers are good examples of how complex technology can be refined and packaged to provide easy-to-use functionality.

In any event, it is likely that the emergence of high quality, low cost manufacturing systems will lead to great changes in how consumers shop, in the world-wide distribution of manufacturing capability, and in a company's supply chains. Lead-times on designing and ordering products will decrease greatly.

Customer-Based Design

If the scenarios outlined above come to fruition, the bottlenecks in the product development-to-product-delivery process for customized products will be 1) preparing the raw materials, and 2) designing the customized product. One advantage of mass production is the ability of the product development organization to ensure the proper design and engineering of the product before it is manufactured. With delivery times of 1 hour or up to several days, it will not be possible for product development organizations to engineer customized products for individual customers. Rather, the entire product development system must be designed to enable very short turn-around times.

Design tools will need to be greatly improved. Tools must be developed that enable customers to specify their desired product, including whatever customizations they desire. The Dell Computer web-site is a good example of a customer-driven product specification interface. However, the customer selects from just a few alternatives for perhaps a dozen main components and/or capabilities. No 3-D layout is performed and no customization of geometry is possible. New types of design tools and user interfaces are needed to enable customers or technicians to describe the specifications of a product and have those specifications converted into operating instructions for an AM system.

Summary Statements

In summary, the capability to process material in an additive manner will enable new devices that could not be manufacturing using conventional technologies. Furthermore, this capability will drastically change some industries. Manufacturing capability will become very distributed, enabling local production of customized products. AM technologies will change how consumers interact with product development organizations. It may cause greater changes in many types of retail settings, if customers want to customize products.

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2.4

Future Trends in Machine Tools and Controls and their Potential Impacts on U.S. Manufacturing

Steven Y. Liang¹

Machine-tooling is a traditional and old industry. Despite its age, even today the industry has a tremendous amount of impact on global economy.

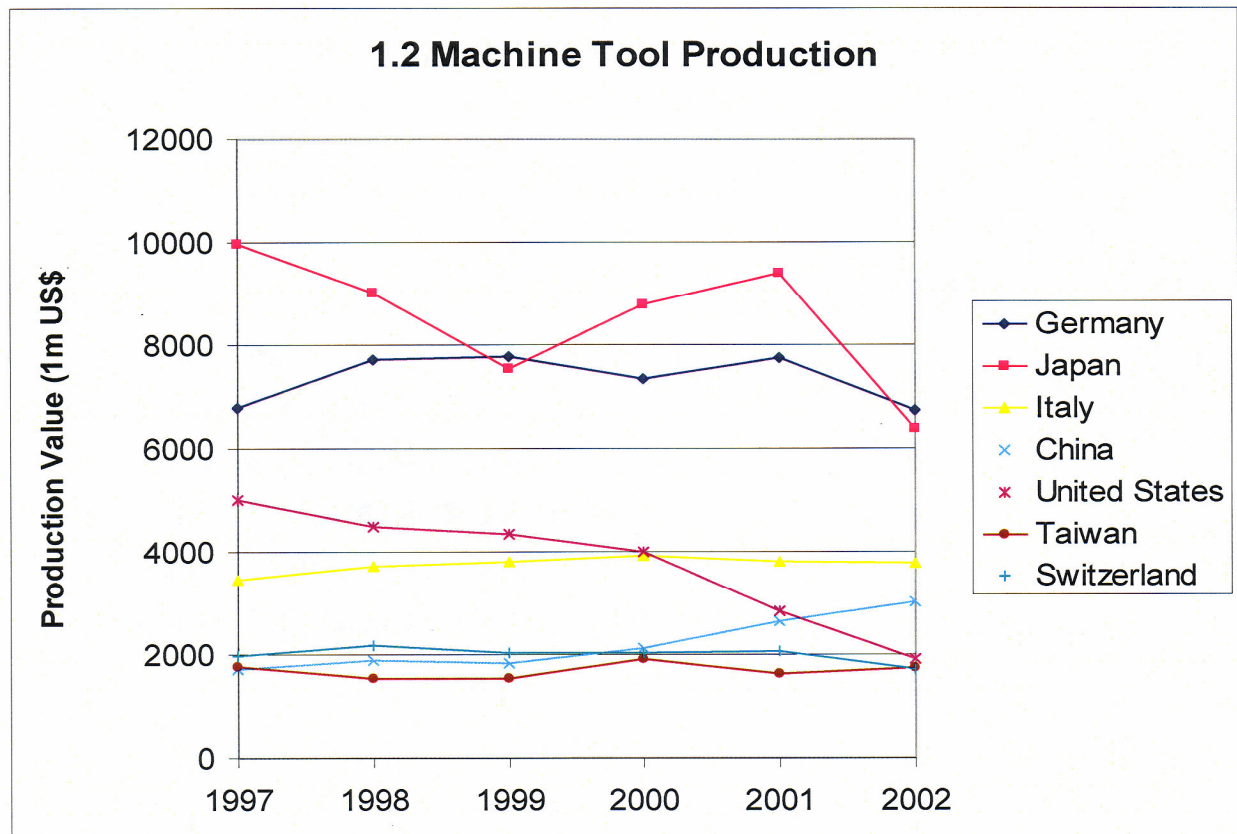
What is a machine tool? In a narrow sense, a machine tool is equipment for machining, like milling boring, etc. In a broader sense, it is production or manufacturing equipment

The widely-accepted official definition of machine tools runs as follows: “Machine tools are machines provided with a power source, for the most part are non-portable, and are used for a variety of **production** procedures, with the aid of physical, chemical or other processes. [...] Machine tools bring the interacting **tool** and **work** together in such a way that after defined relative motions between them, a geometrically definable work-form results at the end of the production process” (DIN 69651).

This definition is accurate, yet the precise definition of a machine tool still will depend on the context of discussion. Considering the economic impact machine tools have, one may pay attention to the fact that there are over 2,500,000 people in the U.S. who use machine tools for living, about 50% of them are in cutting and forming sectors. It is also important to note, that these workers present the most economically vulnerable population group. In terms of dollar amount, manufacturing of metal cutting machines amounts to \$1.8 billion just in the U.S. alone. This is a significant sum of money. Yet, this figure is 60% below the previous U.S. levels. Earlier, the total tool manufacturing accounted for \$5 billion in production value; now it is at \$2 billion.

This number does not include original equipment manufacturers (OEMs). Today, most of the worldwide production of vertical machining is done in Taiwan. The U.S. is no longer a major player in producing machine tools. Germany and Japan share the second largest share of world production, yet both are showing sizeable drops (Figure 2.4.1).

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Source: MMS Online; Gardner Publications, Inc.; 2002
Figure 2.4.1.

If one compares exports and imports of machine tools in various countries, the U.S. is not a strong player again. China is the 4th machine tool producer, but the 1st importer. Japan manufacturers use mainly their own machines for production, hence the country's imports are fairly low, and the Japanese are quite moderate in exporting.

Further, comparisons between 2001 and 2002 production figures are even more alarming. The U.S.A. has experienced the world's largest drop in machine tools production. From 2001 to 2002 the drop was almost 36%. This constituted the largest drop in one year in the world. It is expected that 2003 will present even a more alarming picture. Major U.S. companies are closing down: Bridgeport and Ingersoll have closed their doors.

The industry's manufacturing productivity level is disturbing. In the U.S., there was a 40% drop in consumption of machine tools in one year—from 2001 to 2002. Japan experienced an over 50% drop in that year.

In general, the U.S. is slipping in its leadership position. Such losses maybe explained by a number of factors. U.S. manufacturers have persistently increased their share of FDI overseas. Over 300% of U.S.-based capital investments in the last 10 years went offshore, and concurrently, the manufacturing sector lost 2.6 million jobs from 1979 to 1999. Despite the generally increasing level of manufacturing R&D funding, R&D supported by the Federal government has been decreasing continuously. From its almost

70% share of the total manufacturing R&D in the 1960's, Federal funds constitute only 30% in the late 1990's (Figure 2.4.2).

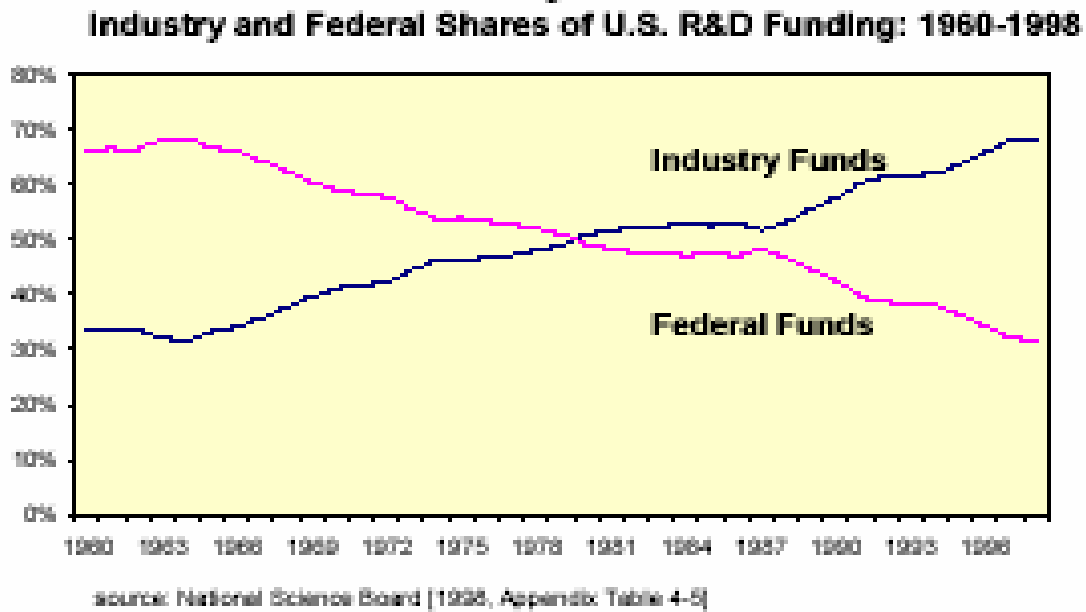


Figure 2.4.2.

Additionally, throughout 1983-1997 manufacturing R&D investments, as the percentage of net sales, had persistently received less than average of total R&D funding compared to other industry sectors. The highest R&D figures are observed for computers and pharmaceuticals. In 1998, pharmaceuticals had the highest R&D share of a little over of 10% of the net industry sales. Computers had a little less than 10% coming in as the second. Manufacturing had only 3% of its total net sales invested in R&D (Figure 2.4.3).

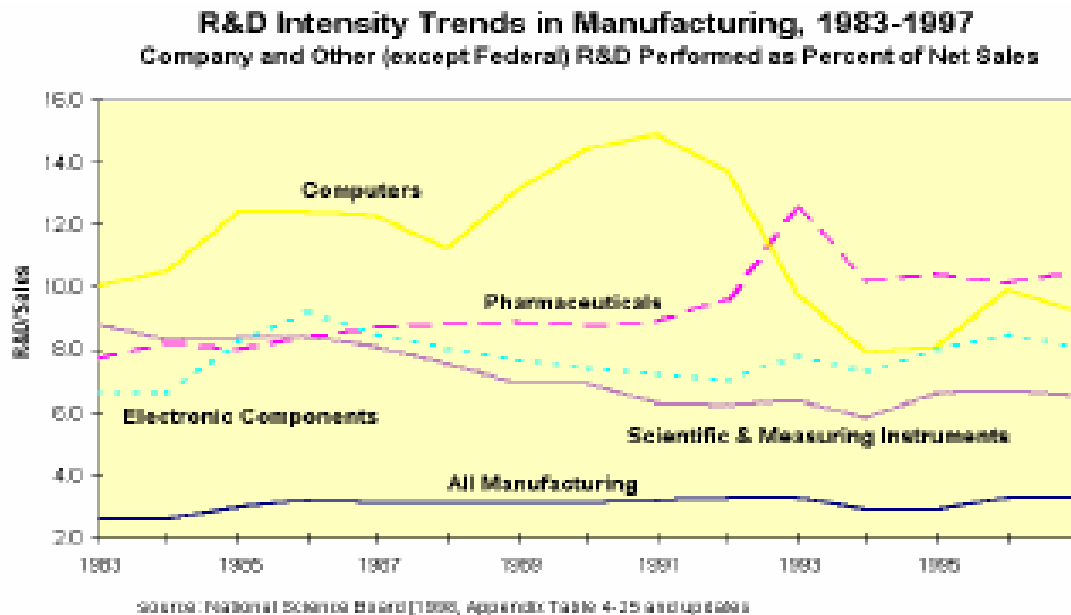


Figure 2.4.3.

Finally, direct labor rate is \$30 per hour in the U.S. vs. \$3 in Eastern Europe, \$2 in China, and \$1 in India, all per hour of labor (Figure 2.4.4).

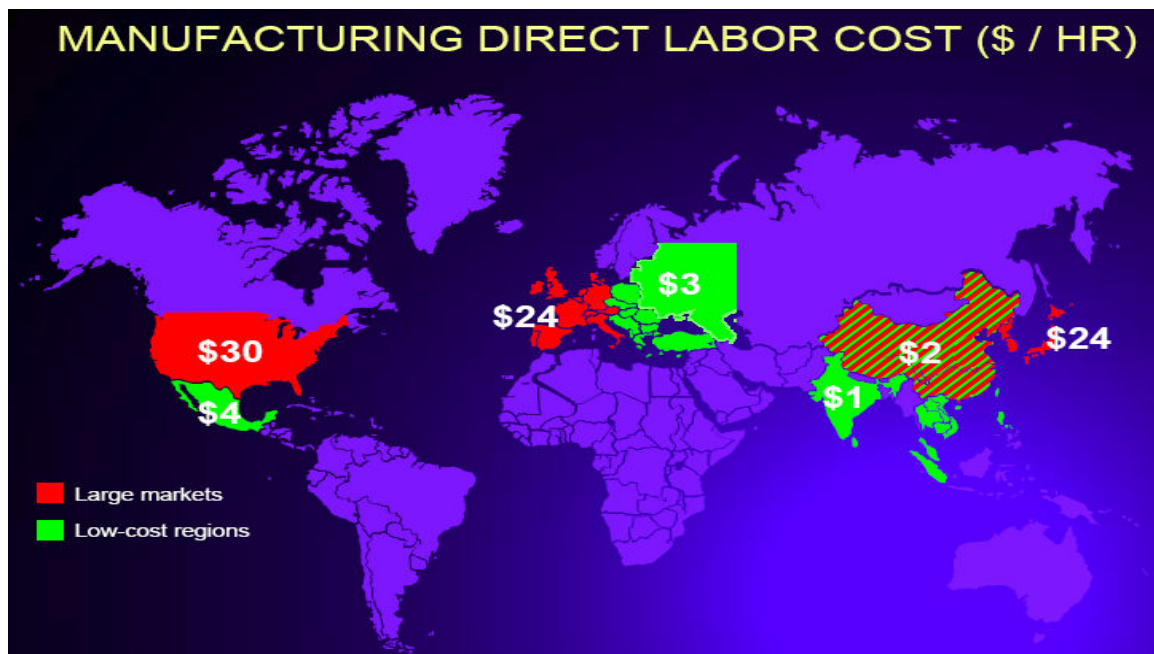


Figure 2.4.4.

Are there any hopes that we may be able to revitalize the sector? Innovation is named to be a driving force of rejuvenation of the manufacturing sector. Alan Greenspan in his congressional testimony on July 15, 2003 pointed out that: "Innovation by its very nature is unforecastable. What we do know is that if we have a sufficiently flexible labor market and a capital goods market, which is functioning appropriately, that jobs will be created."

To summarize, the main tasks for manufacturers are to focus on manufacturing R&D and innovation. There are some examples of what can be done to foster development in these two directions. For example, the Precision Machining Research Consortium (PMRC) at Georgia Tech is involved in four specific areas critical to the progress of manufacturing innovations in general: compliance control in precision grinding, precision compensation for cutter runout, microscale free-form magnetoabrasive machining, and microscale machining and machine tools.

At the moment, compliance control in precision grinding research is focused on establishing open-architecture machine tool controller. This enables grinding process modeling, sensing and overall control. For instance, to improve compliance control of vertical grinding machine we attempt to alter axial force. This permits instantaneous grind so that surface can be much more closely regulated. Hence, sensing and controls can bring down surface flatness by 90+%.

The second area of our research is focused on attaining precision for cutter runouts. In machines, cutter runouts result from spindle wobbling, offset pocket, inset irregularities,

tool wear, uneven inertia, etc. This results in loss of precision and ultimate tool performance. With use of PC device (programming), we can compensate for runoff for special set of cutting conditions. As a result, surface precision/accuracy improves by 70-80%.

The third area of PMRC research is focused on microscale free-form magnetoabrasive machining. The traditionally large grinding hub prevents small material grinding in concave locations. With such tooling, grinding a single particle presents a challenge. If one can suspend a worked-on particle and force it to rotate magnetically, one can cut it to any free-form, which in turn improves precision.

Finally, one last example is the microscale machine tooling. The attempt is to make tools as miniaturized as possible. We can turn a 3x3 meter device into a 100-150 millimeter tool, which presents a 8,000-10,000 times miniaturization. Among the resultant benefits are: space-saving and enhanced precision.

To conclude, the three main points on machine tool manufacturing are:

- Machining and machine tools will continue to be a principal means by which wealth is created;
- U.S. machine tool industry has to dramatically change to stay responsive and competitive; and
- The hope is on new technologies, new products, and new processes resulting from innovative research and development through collaborations between industry, government, and academia.

Discussion of Panel Presentations. Technological Opportunities to Develop New Capabilities: Manufacturing, Strategic Engineering, Adaptive Technologies, and Controls

Thursby. Dr. Liang, one of your slides showed a downturn in world production. At the same time, an improving world economy would indicate a different picture of manufacturing at the global scale. Could you comment on this disparity? Also, where are the primary customers of your research located—within or outside of the U.S.?

Liang. That was a macroeconomic issue. More than 50 percent of the manufacturing downturn is driven by the U.S. economic downturn. All PMRC [research center] customers are in the U.S. However, they may have their tool manufacturing facilities elsewhere.

Danyluk. Professor Rosen, how large would be the share of currently manufactured products that could be produced using stereolithography?

Rosen. Approximately 5%.

Shapira. And how costly it is to implement stereolithography manufacturing?

Rosen. A typical stereolithographical machine costs approximately \$50,000. Our expectations of how the machine will perform and how well it will be adapted to the market could be paralleled with the early experiences of fax machines and computers, which at one time were believed unattainable and very expensive for the consumer market. Within years, faxes and computers have become normal consumer goods. Similarly, we can expect or suggest that the stereolithographic machines may become a part of household equipment.

Shapira. To summarize this panel's presentations, there are broad economic and industrial trends, including mass customization and off-shoring, which are already apparent. We also see the emergence of very specific new micro technologies. Where is the policy area to act upon?

Mistree. As a university, our mission should not be to create technology that goes into the marketplace. Instead, we should be using these technologies as a learning laboratory to train our students. This depends on the principles that one accepts. Why are we bucking the trends of free trade? If you look at the numbers: \$2 per worker, \$1 per worker. Perhaps we should invest in Africa, where labor is 20 cents, which also would mean to invest in the global view of mankind. We must take a systemic perspective. We must accept the notion of free trade that 'the customer is right,' then take a systemic, global view.

Tannenbaum. Professor Mistree, you are absolutely right that we in the U.S. are fortunate that we live in a prosperous society. Trends may better our situation. But given

that it is a global industrial society, we have to look at the impacts of new technologies and globalization on other parts of the world because the ramifications can be destructive in terms of population shifts, etc. Technology is a knife with two edges.

White. Dr. Liang, what is your opinion of the impact of best practices on your industry and the different type of practices in Japan vs. what was considered best practice in the U.S.? How has 'lean' thinking had an impact on the machine tool industry, on the loss of the U.S. market share to Japan and Germany?

Liang. The short-term impact was negative. Yet, we hope that in the long-term the impact will be positive because of the return on innovation. We should not give up on those advanced practices.

Shapira. The entire idea of distributive web based manufacturing presents an intriguing scenario. Where will 'distributed manufacturing' be sited in the future? To what extent will any of it be in the U.S. and what do we need to do to keep manufacturing locations here?

Danyluk. That is where companies are going—they are working toward a distributed model. That is why companies are going to Romania, China, etc. The U.S. will basically have to live with that. We're trying to develop tools and models to optimize and make robust systems to affect that integration.

Shapira. Putting this together with David's paper, perhaps new manufacturing will move closer to customers – so there must be a future for the U.S. But how do we put production and the customer together?

White. This depends on the customer—one customer may want a car in three days, another in two weeks. A three-day order will dictate production at a closer location; a two-week order will let use remote production sites.

Rosen. Cost efficiencies are critical for a commodity that is mass-produced like DVDs. But if you are buying a \$500/piece hearing aide, you want it to fit. Some people will pay a premium to get it fast and customized to their specific needs. Then, traditional things may continue to go in the other direction. Another interesting question is that maybe supply chains will be next.

Ku. There is no need to locate a manufacturing facility near the customer because of today's fast and effective shipping. My daughter ordered a Mac Ipod, which had to be shipped from Shanghai. It came the next day as though it was shipped from the other side of Atlanta. Location does not matter anymore because transportation is so good. If we ship medical devices, it should not matter whether they come from overseas. For most of suppliers in our field, location is becoming less relevant. For most medical device manufacturers, margins are high. They can afford the local, high-wage labor. Counterbalancing forces include whether you trust a product shipped from Sri-Lanka or

Switzerland? Also, there are language barriers. For example, I do not speak Spanish. It is easier for me to hire someone in Atlanta whose margins are five times higher.

White. What you say is certainly true for high value items. In automobile manufacturing, it turns out that best practice is to put the assembly plant in the market. It is better to assemble not for export but for the market. Now the supplier base is all over the world, and the supplier base in the U.S. is near the assembler.

3

Panel on Technological Opportunities to Develop New Capabilities: Microelectronics, Nanotechnology, Medical Devices

Session Chair: Marie Thursby (MGT)

3.1

Technological Prospects for Microelectronics

Jim Meindl¹

The future prospects of microelectronics can be described in a single word:
nanoelectronics.

The most important economic event of the 20th century was the information revolution. It has given us the personal computer, the pocket cell phone with e-mail capability and a digital camera, the electronic wrist watch, medical x-ray tomography, smart weapons, pilotless aircraft, satellite communications and the internet as well as countless other electronic marvels.

The principal driver of the information revolution has been the silicon microchip. Why? From 1960-2000 the number of elementary electronic switches or transistors manufactured in one silicon chip, smaller in size than a finger nail, increased from a handful to approximately one billion. Concurrently, the speed of operation of a chip increased by a factor of approximately one thousand! This combination provided about a one trillion times improvement in functional capability while the manufacturing cost of a chip remained virtually constant!! This unprecedented advance in technology and productivity was *the* prime cause of the information revolution that has almost incredibly transformed our daily lives. How was this advance achieved?

From 1960-2000 the minimum feature size of a transistor (i.e. the smallest feature of a transistor that is visible when it is viewed through an optical microscope) within a microchip was reduced in size from approximately 25 micrometers to 0.25 micrometers. (To provide a point of reference, the diameter of a human hair is about 100 micrometers.) This in itself enabled an increase in speed of 100 times and a reduction of 10,000 times in the amount of silicon real estate occupied by a transistor and consequently its cost. Extraordinary size reduction was *the* primary factor leading to the cost reduction and productivity improvement of microelectronics. In addition, transistor size reduction

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enabled more than a 10,000-fold decrease in the amount of energy dissipated by a transistor in a binary switching transition, the canonical computing operation. Absent this decrease, the temperature rise in a microchip containing many millions of transistors would have been prohibitive.

A second factor that contributed enormously to manufacturing cost reduction was an eight times increase in the diameter of a silicon wafer from 25 millimeters in 1960 to 200 millimeters in 2000. In chip manufacturing a single “wafer” of silicon about 2 millimeters thick and containing many hundreds of chips is handled as a unit until it is fully processed at which time it is diced into individual chips. Consequently, an eight times increase in diameter corresponding to a 64 times increase in wafer area results in greatly reduced manufacturing cost. Parenthetically, I would like to observe that a 200 millimeter or eight inch silicon wafer is “sliced” from an ingot of silicon (in a manner rudimentarily similar to slicing a loaf of bread) that is roughly eight inches in diameter and over four feet in length. The ingot is a single crystal of the element silicon with the atoms virtually perfectly arranged in a cubic lattice that is *self-ordered* as the ingot is grown from a molten pool of silicon contained in a ceramic crucible. *This ingot may be the largest self-assembled nanostructure that is manufactured at this time.* Only man and large animals appear to exceed it in size among self-assembled structures!

Future prospects for silicon microelectronics continuing to serve as the principal driver of the information revolution depend largely on sustaining the dominant trends of the past four decades in transistor minimum feature size reduction and silicon wafer diameter increase. Can these trends continue? Past experience and the laws of physics suggest that minimum feature size now at 100 nanometers (one nanometer is one-billionth of a meter) can continue to scale down for almost 20 years longer at which time minimum feature size will be approximately 10 nanometers. To underscore the nanoscale of current 100 nanometer transistors, the thickness of the insulation layer that separates the input or control electrode from the output terminal of such devices is now about *one* nanometer in thickness. In addition, silicon wafer diameter of 300 millimeters for 2004 cutting edge manufacturing lines is projected to grow to 450 millimeters within the next decade or so. This relentless scaling down of transistor minimum feature size to the 10 nanometer range and scaling up of silicon wafer diameter to 450 millimeters strongly suggest that silicon chips containing approximately one trillion transistors or terascale integration will be in volume manufacturing by year 2020. It is interesting to speculate about what may follow.

To suggest one possible scenario for nanoelectronics that might transpire beyond 2020 it is revealing to introduce a striking analogy between steel as the principal structural material of the industrial revolution and silicon as the principal electronic material of the information revolution. Figure 3.1.1 is a graph whose vertical axis represents tons of steel produced, extending from zero to one billion tons, and whose horizontal axis represents calendar year, extending from 1900 to 2000. The upper locus indicates world production and the lower one U.S. production. The salient point to observe is that throughout the entire 20th century world steel production increased essentially monotonically. Silicon microchip production has followed this trend throughout the past

four decades and it is plausible that this growth will be maintained throughout the first half of the 21st century and perhaps longer.

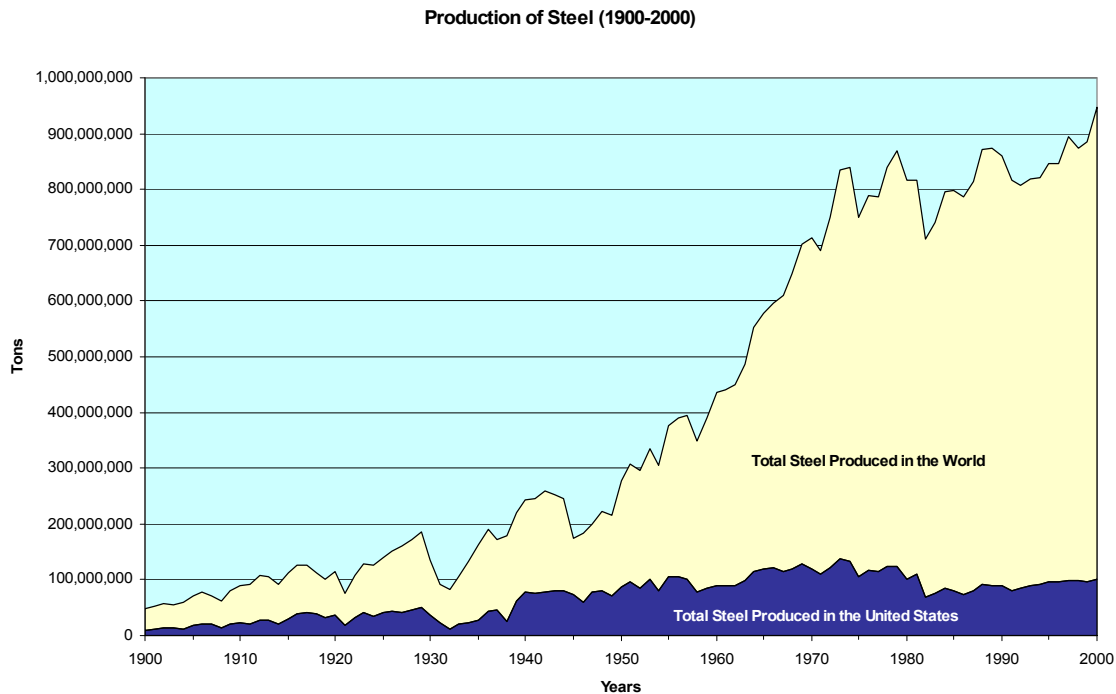


Figure 3.1.1. Steel Analogy.

Moreover, history further suggests that sometime during the next half century, a revolutionary new technology, perhaps even a biotechnology, will be discovered and that it will initially supplement and eventually replace silicon nanoelectronics. A historical precedent for this forecast is the virtually total replacement of the vacuum tube, which literally enabled the birth of electronics during the first half of the 20th century, with transistor electronics and then the microchip after 1960.

In summary, the technological prospects for nanoelectronics and the information revolution that it drives are simply fantastic.

The leading countries in the production of silicon are Taiwan and South Korea. But the derivative of manufacturing silicon is in Eastern China. There is a big effort to keep silicon in the US; a few countries are intentionally keeping silicon manufacturing in the U.S.—Intel, IBM, Texas Instruments.

3.2

What is Nanotechnology? And How Will This Small Wonder Make a Big Change in Manufacturing?

Zong Lin Wang¹

What is nanotechnology?

In the history of industrial engineering, technology characterized by length only occurred in microelectronics, but now we have nanotechnology. How small is one nanometer? The typical width of a human hair is 50 micrometers. One nanometer is 50,000th of a hair width.

Nanotechnology is the construction and use of functional structures designed from atomic or molecular scale with at least one characteristic dimension measured in nanometers. Their size allows them to exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes because of their size. When characteristic structural features are intermediate between isolated atoms and bulk materials in the range of about one to 100 nanometers, the objects often display physical attributes substantially different from those displayed by either atoms or bulk materials.

Phenomena at the nanometer scale are likely to be a completely new world. Properties of matter at nanoscale may not be as predictable as those observed at larger scales. Important changes in behavior are caused not only by continuous modification of characteristics with diminishing size, but also by the emergence of totally new phenomena such as quantum confinement, a typical example of which is that the color of light emitting from semiconductor nanoparticles depends on their sizes. Designed and controlled fabrication and integration of nanomaterials and nanodevices is likely to be revolutionary for science and technology.

Nanotechnology can provide unprecedented understanding about materials and devices and is likely to impact many fields. By using structure at nanoscale as a tunable physical variable, we can greatly expand the range of performance of existing chemicals and materials. Alignment of linear molecules in an ordered array on a substrate surface (self-assembled monolayers) can function as a new generation of chemical and biological sensors. Switching devices and functional units at nanoscale can improve computer storage and operation capacity by a factor of a million. Entirely new biological sensors facilitate early diagnostics and disease prevention of cancers. Nanostructured ceramics and metals have greatly improved mechanical properties, both in ductility and strength.

¹ Zong Lin Wang is a Professor at the School of Materials Science and Engineering and Director at the Center for Nanoscience and Nanotechnology as well as the Electron Microscopy Center at the Georgia Institute of Technology in Atlanta, GA.

From the fundamental units of materials, all natural materials and systems establish their foundation at nanoscale; controlling matter at atomic or molecular levels means tailoring the fundamental properties, phenomena, and processes exactly at the scale where the basic properties are initiated. Nanotechnology could impact the production of virtually every human-made object – from automobiles and electronics to advanced diagnostics, surgery, advanced medicines, and tissue and bone replacements. To build electronic devices using atom-by-atom engineering, for example, we have to understand the interaction among atoms and molecules, how to manipulate them, how to keep them stable, how to communicate signals among them, and how to face them with the real world. This goal requires new knowledge, new tools, and new approaches.

Much more than miniaturization

To many people, nanotechnology may be understood as a process of ultra-miniaturization. Philosophically, changes in quantity result in changes in quality. Shrinkage in device size may lead to a change in operation principle due to quantum effect, which is the physics that governs the motion and interaction of electrons in atoms. In fact, the trend in product miniaturization will require new process measurement and control systems that can span across millimeter-, micrometer-, and nanometer-sized scales while accounting for the associated physics that govern the device and environment interaction at each specific size scale.

To consider the interactions among atoms in the nanometer scale, we need to introduce quantum mechanics and each atom has to be treated as a unit. To face the atoms with the real world in the million-meter scale, we need to consider the collective properties of millions and millions of atoms, so that the matter is considered to be a continuous medium, and we use classical mechanics. The bridging of the two length scales requires new standardized architecture definitions that support multiple physics-based models and new computational representations that allow seamless transition and traversing through these various models.

Manufacturing nanomaterials

Nanomanufacturing technologies that will support tailor-made products having functionally critical nanometer-scale dimensions are produced using massively parallel systems or self-assembly. The current research mainly focuses on nanoscience for discovering new materials, novel phenomena, new characterization tools, and fabricating nanodevices. The future impact of nanotechnology to human civilization is manufacturing. The small feature size in nanotechnology that limits application of well-established optical lithography and manipulation techniques causes industrial nanomanufacturing to remain a serious challenge to our technological advances.

Synthesis of nanomaterials is one of the most active fields in nanotechnology. There are numerous methods for synthesizing nanomaterials of various characteristics. An essential challenge in synthesis is controlling the structures at a high yield for industrial applications. Techniques are needed for atomic and molecular control of material building blocks, which can be assembled, used, and tailored for fabricating devices of multifunctionality in many applications.

The oxide nanobelt discovered in my laboratory is an example (Figure 3.2.1). Ultra-long nanobelts have been successfully synthesized for a wide range of oxides by simply evaporating the desired commercial metal oxide powders at high temperatures. These materials are semiconductors with important applications in sensors and transducers. The as-synthesized oxide nanobelts are pure and structurally uniform; they have a rectangular-like cross-section. The semiconducting oxide nanobelts could be doped with different elements and be used for fabricating nanometer-sized sensors based on the characteristics of individual nanobelts, which could be potentially useful for in-situ, real-time, and remote detection of molecules, cancer cells, or proteins based on electronic signal. The nanobelts could also be used for fabrication of nanoscale electronic and optoelectronic devices because they are semiconductors.

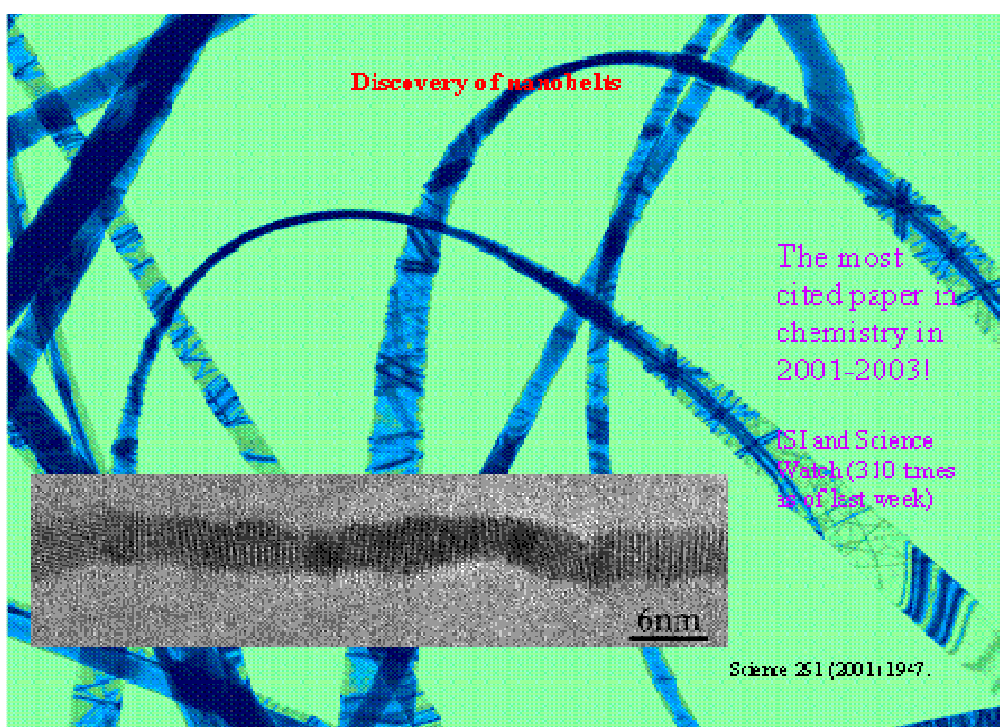


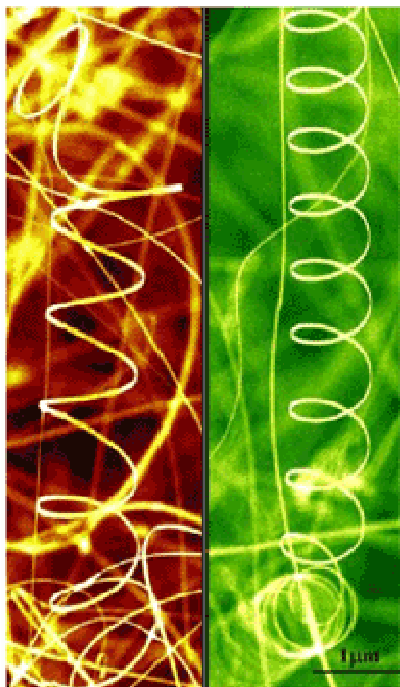
Figure 3.2.1. Discovery of Nanobelts.

Recently, helical nanostructures and nanorings have been grown by rolling up single-crystal zinc oxide nanobelts (Figure 3.2.2). This spiral structure is only possible with the thickness of the nanobelt extremely small. The nanobelts are likely to be an ideal system for understanding piezoelectricity and polarization-induced ferroelectricity at nanoscale; and they could have applications as one-dimensional nanoscale sensors, transducers, and resonators. The next step is to develop techniques for producing large quantities of nanobelts.

Characterizing the performance and properties of nanostructures

Property characterization of nanomaterials is challenging because of the difficulties in manipulating structures of such small size. New tools and approaches must be developed to meet new challenges. Due to the high size and structure selectivity of nanomaterials,

their physical properties could be quite diverse, depending on their atomic-scale structure, size, and chemistry. A typical example is the carbon nanotube, which is made of concentric cylindrical graphite sheets with a diameter range from one to 400 nanometers and length of a few micrometers. Characterizing the mechanical properties of individual nanotubes, for example, is a challenge to many testing and measuring techniques because of the following constraints. First, the size (diameter and length) is rather small, prohibiting the application of well-established testing techniques. Tensile and creep testing require that the size of the sample be sufficiently large to be clamped rigidly by the sample holder without sliding. This is impossible for one-dimensional nanomaterials using conventional means. Second, the small size of the nanostructure makes their manipulation rather difficult, and specialized techniques are needed for picking up and installing individual nanostructures. Therefore, new methods and methodologies must be developed to quantify the properties of individual nanostructures.



In-situ transmission electron microscopy technique, or TEM, has been developed for measuring the modulus of individual carbon nanotubes. We have to see the object while its properties are being measured, thus, a microscope is required. To carry out the property measurement of a nanotube, a specimen holder for a TEM was built for applying a voltage across a nanotube and its counter electrode. To measure the bending modulus of a carbon nanotube, an oscillating voltage is applied on the nanotube that can tune the frequency of the applied voltage. By changing the frequency of the applied voltage onto the nanotube, mechanical resonance can be induced in carbon nanotubes at specific frequencies from which the bending modulus can be derived (Figure 3.2.3). This type of technique works well for small objects.

Figure 3.2.2. Spiral Structure of Nanobelts.

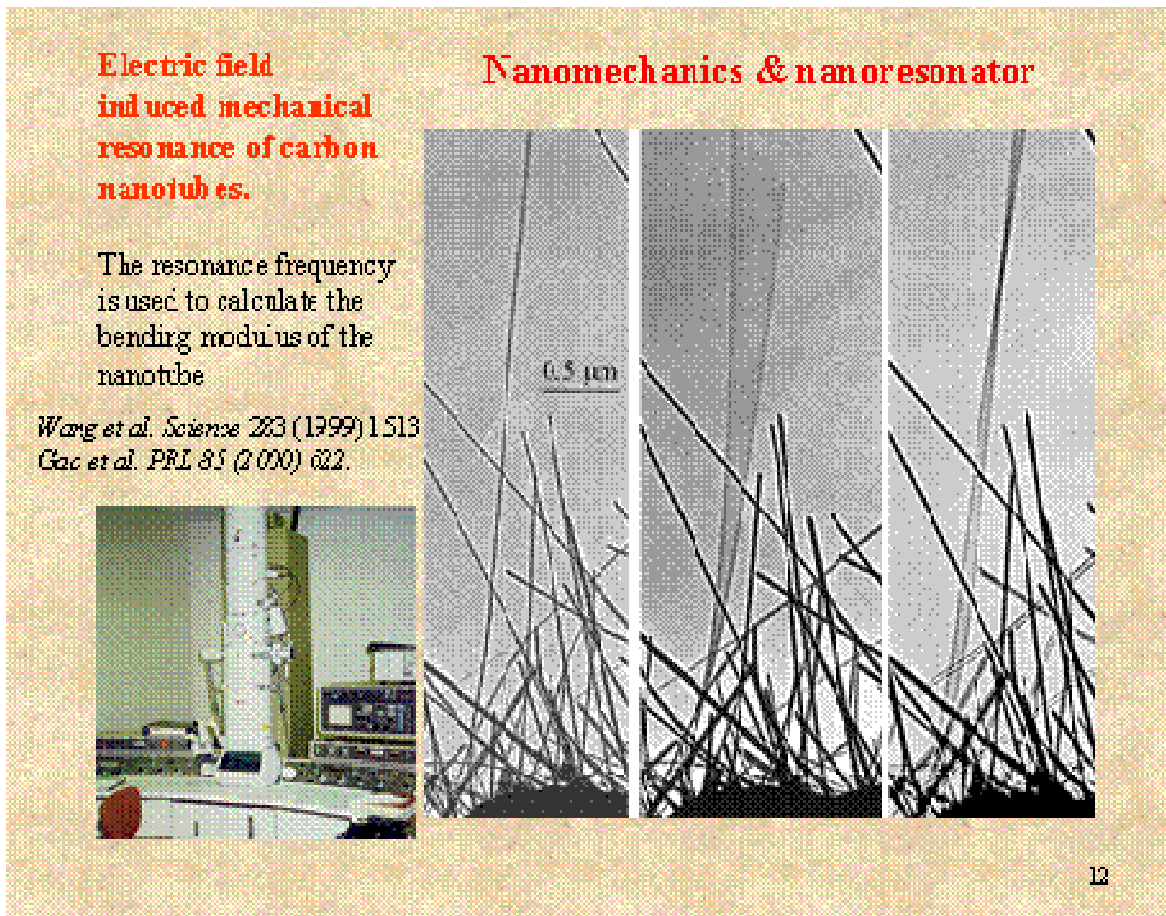


Figure 2.2.3. Nanomechanics and nanoresonator.

Large-scale manipulation and self-assembly

Manipulation of nanostructures relies on scanning probe microscopy. Using a fine tip, atoms, nanoparticles, or nanowires can be manipulated for a variety of applications. This type of approach is outstanding for scientific research. For manufacturing, an array of scanning tips, if synchronized, may be used for achieving atom-by-atom engineering. But the building rate is rather slow. If a device has a feature size of five nanometers and a scanning tip can move atoms 10^9 atoms per second, it will take about six months to build 10^{12} devices on an eight-inch wafer.

The ultimate solution is self-assembly. Like many biological systems, self-assembly is the most fundamental process for forming a functional and living structure. The genetic codes and sequence built in a biosystem guide and control the self-assembling process.

Self-assembly is the organization and pattern formed naturally by the fundamental building blocks such as molecules and cells. Designed and controlled self-assembly is a possible solution for future manufacturing needs. Figure 3.2.4 is an example of the self-assembly of magnetic nanoparticles for achieving ultra-high memory density.

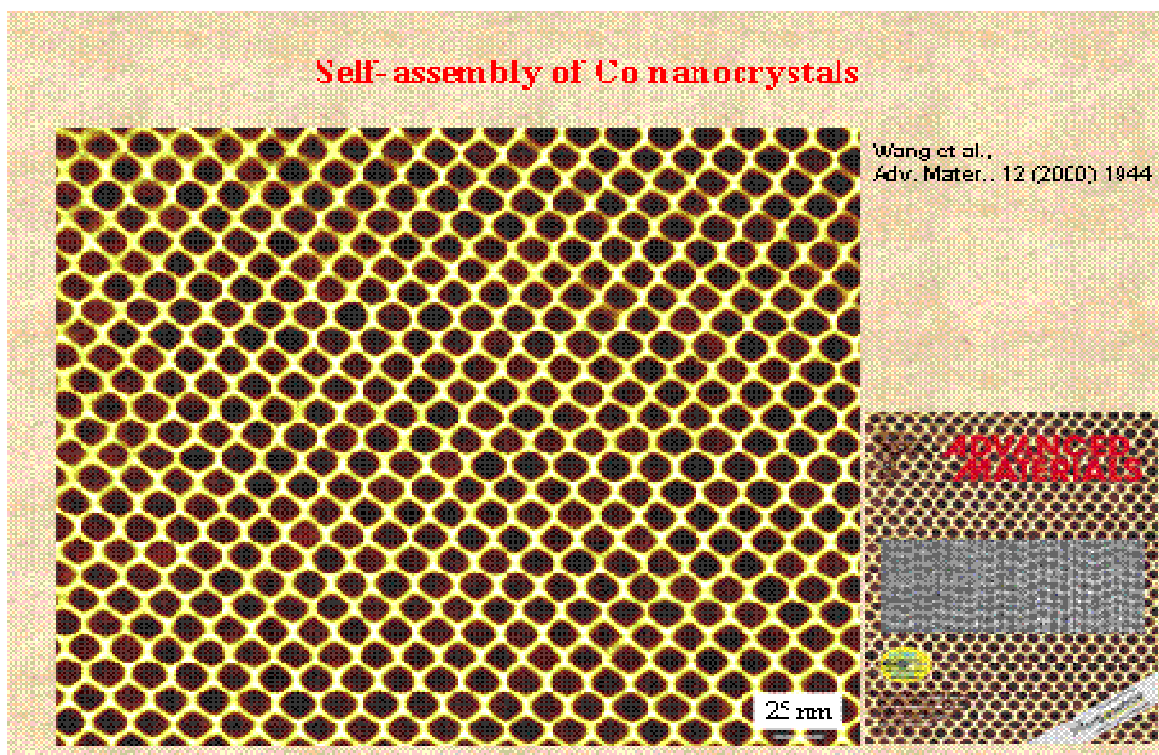


Figure 3.2.4. Self-assembly and Co Nanocrystals.

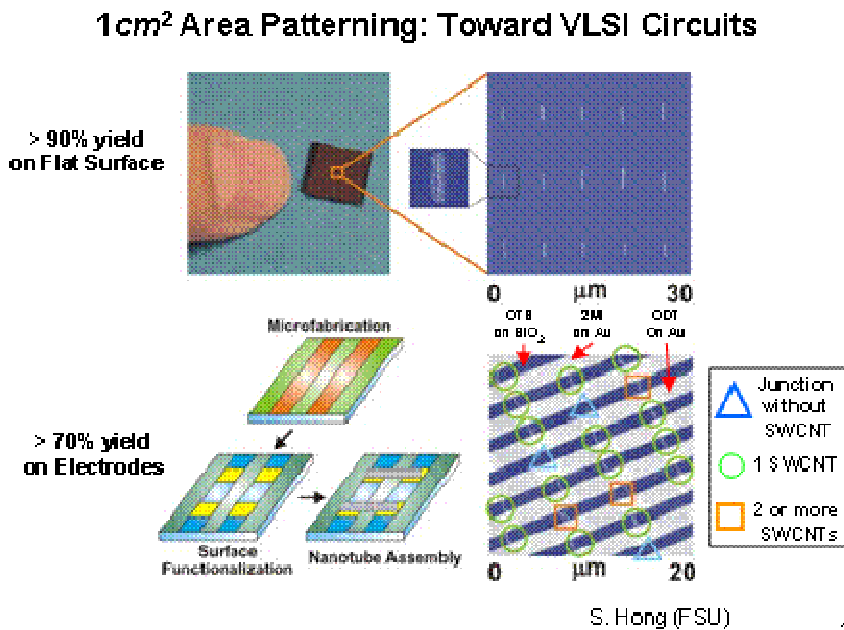
Size- and shape-selected nanocrystals behave like molecular matter that can be used as fundamental building blocks for constructing nanocrystal-assembled superlattices. Self-assembled arrays involve self-organization into monolayers, thin films, and superlattices of size-selected nanocrystals encapsulated in a protective compact organic coating. Nanocrystals are the hard cores that preserve the ordering at the atomic scale; the organic molecules adsorbed on their surfaces serve as the interparticle molecular bonds and as protection for the particles in order to avoid direct core contact with a consequence of coalescing. The interparticle interaction can be changed via control over the length of the molecular chains, resulting in tunable electronic, optical, and transport properties.

Large-scale parallel device fabrication and system integration

System integration involves at least an integration of numerous functional materials and components for achieving a complex, preprogrammed action. This involves patterned materials growth on a designed substrate; large-scale, parallel integration of nanowires, nanoparticles, and functional groups; interconnection among the components; and defect-tolerated path design following neuron networks.

A wide range of novel approaches has been developed for fabrication of single nanodevices. Nanomanufacturing requires a simultaneous, parallel fabrication of a large amount of nanodevices under precisely controlled conditions and repeatability. This remains a major challenge to the development of nanotechnology, especially for nanoelectronics. A possible solution is to integrate patterns produced by lithographic technique with self-assembly process. Self-assembly of single-walled carbon nanotubes is one example.

By functionalizing the substrate produced by lithographic technique so that individual carbon nanotubes selectively recognize the locations for self-assemble on the substrate following specific patterns, mass producing carbon nanotube-based circuit structures is possible (Figure 3.2.5). To achieve the process, the substrate was coated with patterns of organic molecules using techniques such as dip-pen nanolithography and microcontact stamping. Two surface regions have been produced: one patterned with polar chemical groups, and the second coated with non-polar groups. A suspension of single-walled carbon nanotubes solution was added, and the nanotubes were attracted to the polar regions and self-assembled to form pre-designed structures. Millions of individual nanotubes have been patterned on stamp-generated microscale patterns, covering areas of about one square centimeter on gold.



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Figure 3.2.5. Carbon Nanotube-based Circuit Structures for Mass Production.

Integrating nanometer-to-millimeter manufacturing technologies

Over the next decade, major industrial and scientific trends that emerged during the 1990s will influence not only how manufacturing will be done, but also what is manufactured. The size of many manufactured goods continues to decrease, resulting in ultra-miniature electronic devices and new hybrid technologies. For example, micro-electromechanical system, or MEMS, devices integrate physical, chemical, and even biological processes in micro- and millimeter-scale technology packages. MEMS devices are used in many sectors: information technology, medicine and health, aerospace, automotive, environment, and energy, to name a few.

The future relies on the integration of nanotechnology with existing technology. The challenge remains in integrating nanotechnology with microelectronics-based technology.

The nanometer-scale components have to be connected with micrometer- and millimeter-scale components to communicate with the real world. This requires an integration of not only the technologies covering nanometer-to-millimeter multilength scales, but also the physics and chemistry covering the entire length scale. We are facing the merging of quantum mechanics and classical mechanics. Any ultra small components have to be connected with the real world. The goal should be on how to use nanotechnology to make microtechnology more efficient, multifunctional, and intelligent as well as faster, smaller, and achieving the impossible. Nanotechnology comes to life if we can achieve the integration of nanoscale building blocks with lithographically produced structures through self-assembly and genetically engineered growth (Figure 3.2.6).

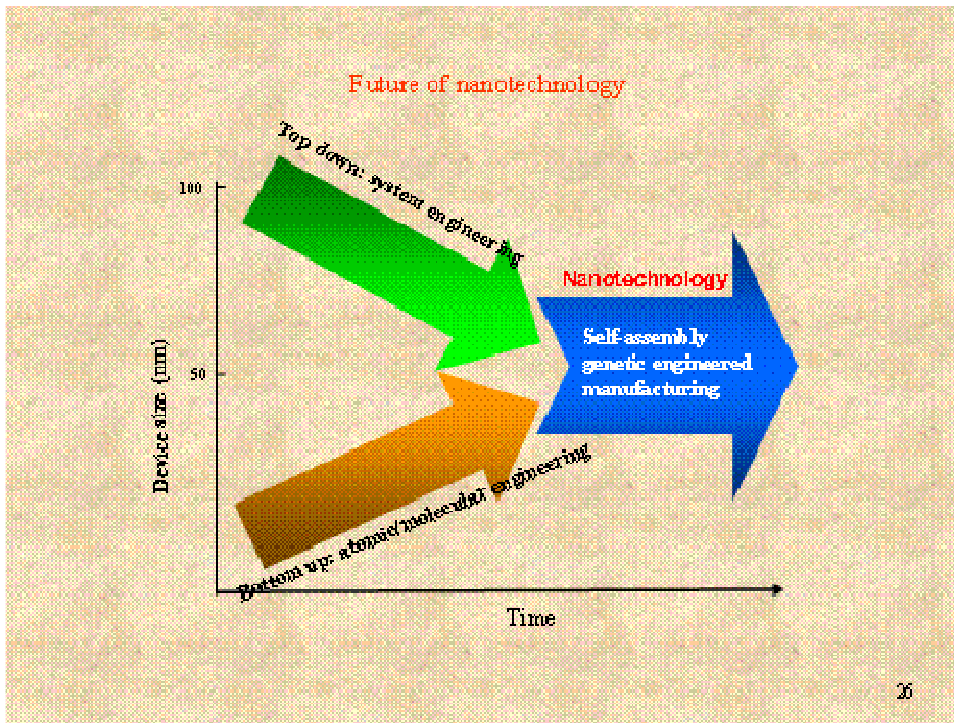


Figure 3.2.6. Future of Nanotechnology.

Bio-inspired manufacturing

As for atomic and molecular control and self-assembly, biological systems are the most extraordinary examples because they have been the most precise, efficient, and complex systems in assembling life species for millions of years. Therefore, the biological system is an ideal model for humans to use in developing a system. Biological engineering is an emerging technology paradigm capable of enabling revolutionary advances in the fabrication of micro- or nano-structured materials and devices. Interface between bio-nanostructures and a bio-inspired structure to produce multifunctional and adaptive nanostructures is a future direction of nanomanufacturing. Biological organisms exhibit unprecedented control at the micrometer and nanometer scales, including:

~Precise genetic control over microscale and nanoscale shapes and features to be produced, such as a biological species.

- ~Direct three-dimensional self-assembly of microstructures and nanostructures (e.g., fibers, tubes, capsules) into functional groups.
- ~Highly selective chemical separation/precipitation (e.g., biomolecular agents can localize the precipitation of solids with tailored functionalities – optical, chemical, mechanical, etc.) to have large quantity materials that are pure enough for advanced technological applications.
- ~Massively parallel replication at ambient conditions (low-cost, environment-friendly processing) for manufacturing purposes

Figure 3.2.7a shows a silica-based nanowire grown in my laboratory using a solid-vapor phase process. In nature, silica-based diatoms can exhibit unique and beautiful shapes, as shown in Figure 3.2.7b. The difference between the two cases is that the manmade nanomaterial has relatively poorer reproducibility and controllability, but the genetically engineered natural materials have precise reproducibility and have been produced at a large amount. Nature is the best example for nanomaterials manufacturing.

The design and manufacture of bio-inspired materials is being realized in a number of ways. The controlled shapes and fine features of lignocellulosic structures may be used to generate new, high-value-added ceramic-, metal-, or polymer-based products. Natural or genetically modified lignocellulosic structures may be cultured, and the structures can be chemically converted into new materials without loss of shape or fine features.

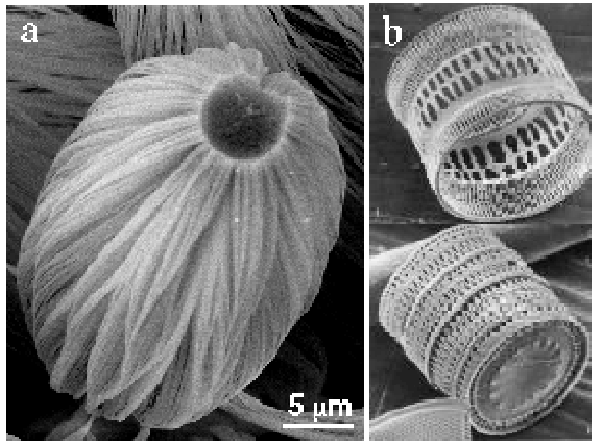


Figure 3.2.7. Genetically Engineered Materials:
A New Paradigm for Manufacturing.

Building nanomanufacturing standards

Nanomanufacturing needs the measurements and standards required to achieve effective and validated nanoscale product and process performance. This challenge is mainly in the following three directions:

Atomic-scale manufacturing: Develop and assemble the technologies required to fabricate standards that are atomically precise. This will include work directed at solving artifact integrity, precision placement, dimensional metrology, and manufacturing issues.

Molecular-scale manipulation and assembly: Identify and address the fundamental measurement, control, and standards issues related to manipulation and assembly of microscale or nanoscale devices using optical, physical, or chemical methods. This entails building the manipulation technology and using it to understand and address the measurement issues that arise when assembling devices at the microscale or nanoscale level.

Micro-to-millimeter-scale manufacturing technologies: Develop the technologies required to position, manipulate, assemble, and manufacture across nanometer-to-millimeter multilength scales.

Not just an engineering process

Traditionally, manufacturing is attributed to an engineering field. For nanomanufacturing, we must go beyond engineering. Once we approach the atomic-scale precision and control, fundamental physics and chemistry have to be applied. The nanoscale manufacturing is multidisciplinary -- involving but not limited to mechanics, electrical engineering, physics, chemistry, biology, and biomedical engineering. The future view of nanomanufacturing is the integration of engineering, science and biology. This complex task requires not only innovative research and development themes, but also a new education system for training future scientists and engineers.

3.3

Advances in Materials and Self-assembly

Rina Tannenbaum¹

I would like to show some applications of nanostructure, then discuss options of how to make them.

Nanoscope dimensions illustrate why making materials at the nanoscale becomes an entirely different way of thinking. When we go from micro and millimeter scale, we make them smaller. We machine them, do things to get to the micron size. But in the nano regime we cannot do that because properties come up. We get surprises – materials that are believed to be nonmagnetic all of a sudden become magnetic. The catalytic properties of other materials alter because the surface properties and reactivities become different. At such a nanoscale regime, size is one of the most fundamental parameters. Small changes in size give large change in reactivity and chemical properties. In effect, we start from nano size and build up to micro size.

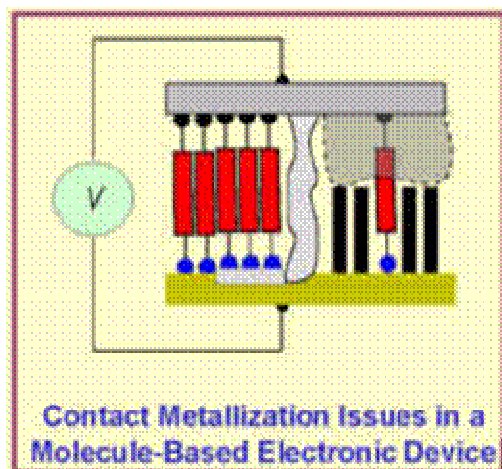
In general, when applying nano technology one needs to know its apriori application, as the entire process is a build up from bottom up on the basis of factor extraction. For example, consider quantum dots first developed at MIT. Different sizes actually exhibit different colors. These are interesting materials-specific functional groups. These molecules are selectively deposited and can be used for molecular recognition in different ways – three-pronged to five-pronged, etc. One of the most important ventures is molecular electronics. This is how we are involved with MARC. We are involved in developing smart glues or other types of applications.

One future application of nanotechnology is development of a nanocomputer. A nanocomputer utilizes nanotubes as interconnections and to replace the transistors of today. This is a rather ‘futuristic’ view (Figure 3.3.1).

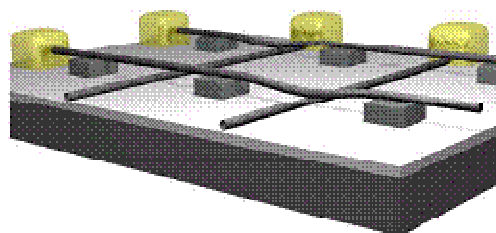
Another application would be drug delivery. Consider particles of synthetic protein, dendrimers. One can control their sizes by building them up step by step in the lab. Additionally, one can tether various other organic molecules, or in effect, functionalities such as a contrast agent or a cancer fighting drug. Based on differences in PH, and other properties one is able to control the release of these agents. Drug delivery is an area where nanotechnology will provide its first breakthroughs (Figure 3.3.2).

¹ Rina Tannenbaum is an Associate Professor at the School of Materials Science and Engineering at the Georgia Institute of Technology in Atlanta, GA.

Applications: Molecular Electronics



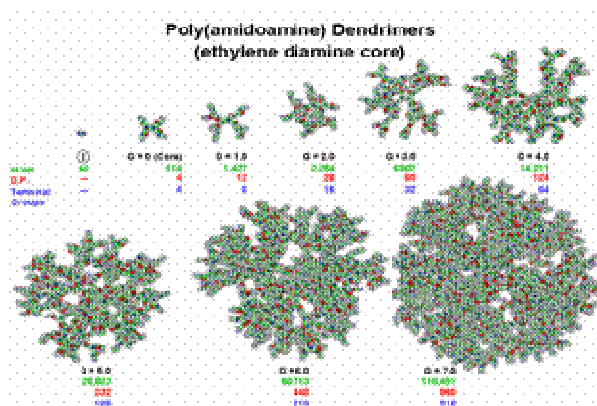
Nanotube Computer



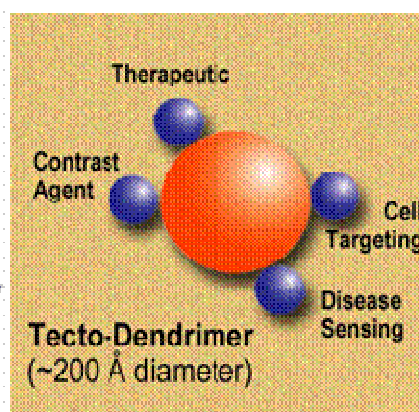
New Paradigms for the Future Nanoelectronic Devices

Figure 3.3.1. Applications: Molecular Electronics.

Applications: Drug delivery



Dendrimer Synthesis



**Dendrimers with Grafted
Functionalities**

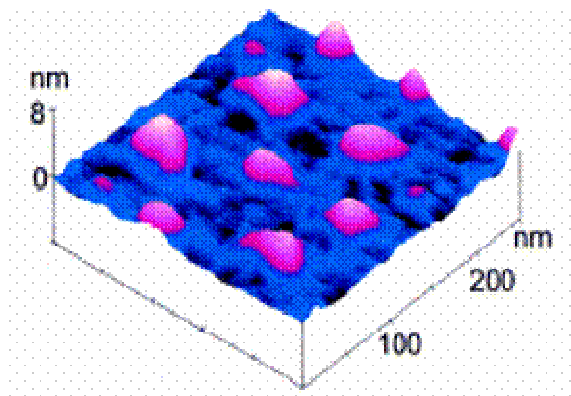
Figure 3.3.2. Applications: Drug Delivery.

Finally, the last application is in optoelectronic materials: created out of block of polymers. The method is ‘alternating blocks of polymers,’ which in effect is changing concentrations and alternatings, thereby creating photonic-bandgap materials and periodic materials for waveguides and grating (See Figure 3.3.3).

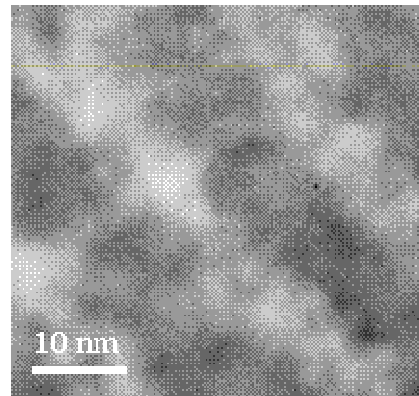
Applications

Opto-Electronic Materials

Based on Block Co-Polymer Templates



***Photonic Bandgap
Materials***



***Periodic Materials
for Waveguides and
Grating***

Figure 3.3.3. Applications: Opto-Electronic Materials Based on Block Co-Polymer Templates.

What are the issues that manufacturing of nanoscale technology, or turning atoms and molecules into nanoscale components and devices will have to consider? There are a number of issues that are specific to nanoscale manufacturing. At the synthesis stage, there are issues that address high chemical specificity, control of size, and control of shape in terms of packing and organization of materials. At the processing stage, the goal is to create fundamental materials by controlling the intermolecular interactions and developing a long-range order while maintaining the specificity and coherence of base structures.

At this point it becomes clear that we are in need of working, robust templates that would enable us to build new materials, or components and devices, at the nano scale. There are two main ways to do it—bottom up and top down. The top-down approach involves lithography, whereas the bottom-up approach is, essentially, chemical self-assembly. My own view on types and modes of templating is that it should be a combination of both lithography and self-assembly.

There are a number of concrete challenges related to nano scale manufacturing that need to be addressed to make nano manufacturing a reality:

- Special manufacturing environment equipment;
- Cost and maintenance of equipment;
- Cost of raw materials – precursors are quite expensive;
- Time scales – some can take days or weeks for nanoscale processes;
- Quality control – how to fix problems in small scale; and
- How to integrate small nano devices into macro world.

3.4

Medical Devices and Global Manufacturing

David Ku¹

I would like to draw your attention to business aspects of technology and manufacturing. The focus of my presentation is on medical devices engineering and manufacturing. Yet, instead of telling you about the engineering mechanics, I will elaborate on the ways that commercial forces change medical devices manufacturing.

Generally, medical technology is not widely discussed. As an industrial sector it tends to be referred to as a 'stepchild' in favor of pharmaceuticals. Despite this unfavorable attitude, medical devices comprise the biggest sector within the entire medical technologies industry sector.

Medical devices exhibit a wide variety of structures and parts. Typically, they are made of metal. Some producers use CNC (Computer Numerical Control) procedures, others manufacture them manually, or combine both computer-controlled as well as manual manufacturing procedures. In essence, manufacturers are faced with equally large costs when choosing between the two methods, with the main reasons for this being the high degree of complexity of produced goods.

Availability of metal machining shops seems to dictate the choice of manufacturing location. The U.S. capital of medical device manufacturing is Gary, Indiana, in Germany, it is Tutlingen.

On the global scale, the sector accounts for more than \$40 billion, or more than biomedical and pharmaceutical industries combined. About one half of the world manufacturing of medical devices are located in the U.S. Once, U.S. manufacturers obtain the FDA approval, they are able to quickly adapt new manufacturing technologies. However, FDA approval procedures are still deemed as a substantial delaying factor.

Manufacturing technologies for producing pills are not expected to change dramatically. However, in the field of medical devices significant advances are observed on a regular basis. For example, today heart pacemakers can be used to control for brain-related Parkinson's disease [need to provide timeframe of when it was not possible, etc. to compare with the conventional practice of today; also, did this change occur due to change in manufacturing technologies; if yes, which mfg technologies?].

Medical devices are much in need for the state of art manufacturing that engineering can offer. For instance, with stereolithography we are able to produce an individually-fit

¹ David Ku is a Professor at DuPree College of Management and School of Mechanical Engineering at the Georgia Institute of Technology in Atlanta, GA.

prosthesis within weeks, instead of the previously usual years. With such technology individual prosthetic body parts can be produced for individual people.

Consider a regular knee pain caused by arthritis. Our body grows cartilage until about puberty and since then the body has to live with what it has in place. It is easily damaged by normal wear and tear, and it does not get replaced. Currently, there are no good materials that can replace cartilage in cases of severe damage. Typically, cartilage is replaced by a metal part.

Today's cartilage replacement procedure leaves much to be desired. The total knee replacement surgery is usually extremely expensive—it costs 50% more than a typical heart bypass surgery. The recovery time is long, it takes anywhere from three to six months for patients to start walking. The operation itself is quite long—3-6 hours. Finally, the metal replacement does not work for everyone—many patients are faced with the prospect of amputation. Despite these drawbacks, the practice is recognized as respectful and millions of people have benefited from it.

The hope is that some new material can diminish the risks that our patients are facing today. Such material has to be compliant with cartilage. For example, arthroscopically-delivered Salubria™ knee cartilage is a lot less invasive and more cost-effective alternative for the metal knee replacement. The product can be literally slipped into a knee within about 15 minutes. The success has been evidenced by several thousand patients who were able to walk the day after the procedure (Figure 3.4.1).

Salubria™ Knee Cartilage

- For all patients with arthritis
- Off-the-shelf device
- Arthroscopically delivered
- Quick recovery

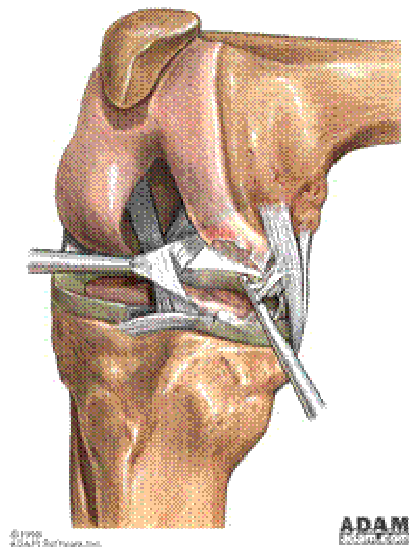


Figure 3.4.1.

At this point, extensive application of Salubria™ requires rapid manufacturing systems that are capable of producing customized products for different types of populations.

To recap/summarize, medical devices present billion dollar markets. Average industry margins range from 60 to 90 percent. Currently, investment climate is quite active for the industry—many of the recent IPO's occurred in medical devices. Return on investments is 10+ times in 5-7 years.

Production of medical devices is rather typical. It consists of metal tooling, polymer processing, the use of electronics and assembly. Employees work in sterile conditions and are typically highly motivated believing that their work saves and/or helps someone's life. The U.S. is well positioned to turn the medical device industry into its competitive advantage.

Consider CIBAVision located in Duluth, GA. The company is the largest world producer of contact lenses. One may wonder—why the company does not outsource its manufacturing facilities? The answer is in the high level of skills of their employees. Additionally, they have to use highly sophisticated equipment and to ensure excellent quality controls. Even one product of lower quality will ruin the company. Given these requirements, it is much safer to have a manufacturing site located nearby. Other companies located in Georgia are: CR Bard and SaluMedica both based in Covington.

Typically, such companies can start from a fairly small scale. In most cases it would be enough to have a small clean room, about 1,000 square feet. Yet, even with only one full shift such operations can generate \$40 million of product per year. This is a high value-added production.

From the standpoint of public policy, local and state authorities may develop incentive plans to attract such companies. For example, Manchester, GA provided Horizon Medical Products, which employs only 100 people, with a free building. In return, the city receives all other employment and service industry benefits.

Atlanta is not yet known for medical devices.¹ Additionally, there is a drive to go offshore. Other attractive manufacturing sites are located in Ireland, almost all major medical manufacturing moved there, Germany, Switzerland, and Japan. The list of countries exemplifies again that medical production is not moving to 3rd world countries.

¹ For helpful info on medical devices industry and its development in Atlanta refer to an article at: http://216.239.37.104/search?q=cache:v7SCgP7DqMYJ:www.bizjournals.com/atlanta/stories/2002/10/21/story5.html%3Fjst%3Ds_rs_hl+CR+Bard+georgia&hl=en&ie=UTF-8.

3.5

Discussion of Panel Presentations. Technological Opportunities to Develop New Capabilities: Microelectronics, Nanotechnology, Medical Devices

Danyluk. Professor Meindl, do you have any idea what will be the next microelectronics technology after silicon?

Meindl. The question on what type of technology will come after silicon is completely wide open. If I had to guess about the technology being pursued, it would be the carbon nanotube for the following reasons: (1) it is a very good conductor; and (2) it can interconnect. The chief determinant is no longer the transistor, it is the interconnect. There was a transition 10 year ago. Interconnects are playing a much more important role. In addition, the nanotube can hook up and make a field effects transistor. Nanotubes also can provide lighting effects, lasers. There is a terrific effort is to use photons. Nanotubes also offer hope to be able to work in three dimensions. Right now we have no hope to do this in semiconductor industry.

Shapira. Dr. Wang, what will the future nanomanufacturing factory look like? How big will this factory be? And, will nanomanufacturing companies be small or large? What will they look like?

Wang. We look at small things. A lot of experts – chemists, electrical engineering, physicists. We need a lot of money, reciprocal space, and future integrative effort. We will have to change our mentality about what manufacturers do today to what they will be doing in five-ten years from now.

Shapira. Let us consider satellites. These require relatively few skilled shop-floor workers to build, but it is a very knowledge-intensive enterprise with thousands of other contributing researchers, designers, systems engineers, programmers, etc. Is this what nanomanufacturing will look like?

Wang. The scale of equipment is about 4 feet costing \$15,000. Each run lasts an hour and a half. Additionally, temperature matters for what products can be manufactured. The production can be scaled up.

Danyluk. Yes, we know how to scale things – scaling laws are well known.

Wang. It is manufacturing, or producing itself that is what we do not know.

Danyluk. Rina, how about the fluid transport method?

Tannenbaum. Yes, there is a potential to use fluid to transport things to surface. This would be a function of residence time of the point on the tip. One can put it, keep it, and lift it. Also, it can be programmed to have the right size of spot and predetermined sizes. One can also change it on the way. It is possible to make a variety of structures on the same surface.

Danyluk. That could be a manufacturing process itself.

Tannenbaum. Yes, there is quite a potential there.

Rosen. Professor Meindl noted that currently the largest self-assembly is the elephant, or the nature. There is a body of work in nano using DNA as a template. Is that likely to be a fruitful area? What are the challenges?

Tannenbaum. The DNA is used largely as a tethered functional group to facilitate assembly of particles. In particular, its use of specificity to create attraction of different particles to assemble in different ways. Yet, DNA is not conducted and that is a problem. One can metalize DNA. There are studies exploring the area and DNA's potential in serving as a template. It is also fashionable to work with the DNA. The field itself is quite fascinating. A lot of people in ceramics are trying to get into the bio world through this door, but using the DNA as a technology is still an unclear area and the area of future research.

Danyluk. What margins would drive anyone from the U.S. to China or Switzerland. For instance, some companies are moving to China for commodity items.

Ku. All companies that do not have brand name, whether producing tubes or other commodity items (exclusion for silicon) are likely to move to China. But none of companies with high-tech products are going offshore.

Rosen. It depends on the distribution of manufacturing, or an analysis of where it would make more sense to produce things. For instance, CIBA, the contact lenses producer, once they complete their product, they send it to Asia to get it packaged and then ship it back here. From this, it seems that our burden is to keep innovation going. Unless we ride the wave of innovation, there will not be much left except in niche areas.

Ku. It is also very useful to put your hands into manufacturing processes. I learned a lot by simply watching people manufacture their product.

4

Organizing Manufacturing to Compete at Global Scales

Session Chair: Steve Danyluk (ME)

4.1

New Opportunities in Logistics: Technology and Trucking

Chelsea White^{1,2}

Due to increased globalization, businesses are managing global supply chains. Information technology and the Internet have introduced new market opportunities. A rise in productivity and increasing cost pressures from global competition has introduced just-in-time manufacturing and assembly. The trucking industry, which moves over three-quarters of the freight in the U.S., has had to adapt to and fulfill the demands to move freight on time, reliably, and with greater visibility. Sophisticated product offerings, globalization, and increased customer expectations make logistics, the managed movement of goods, the key to competitiveness of companies and regions³.

Technology in Trucking

The transportation industry has always strived to move goods farther and faster, thus allowing for better trading opportunities and higher profit from goods. With the advent of air cargo, goods moved greater distances than ever before, but at a very high cost. In the 1980s, U.S. industries started to readily adopt just-in-time manufacturing to reduce inventory, decrease spoilage and increase profits. In the mid-1990s, supply chain management, or flow management, was introduced to help increase profits for companies by again reducing inventory and purchasing only what was needed when it was needed. After the events of September 11, 2001 and other recent disruptions, companies are starting to look at just-in-case policies that allow for extra inventory just in case something unforeseen or unavoidable happens⁴. “Just in case” and “just in time” are largely dependent on the trucking industry, as their success depends to a great extent on the industry’s response to these initiatives.

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² This paper is a summary of the forthcoming chapter “Information Technology in Trucking,” by Anuradha Nagarajan, Enrique Canessa, Will Mitchell, Chelsea C. White III. Maciek Nowak, Anuradha Nagarajan, and Chelsea C. White III participated in the development of this summary.

³ Lahsene, Susie. New Economy, New Vision for Transportation. TR News. September 2001. Pages 9-11

⁴ Farrell, Diana, Terra Terwilliger, and Allen P. Webb. Getting IT spending right this time. The McKinsey Quarterly, 2003 Number 2 available at

http://www.mckinseyquarterly.com/article_page.asp?ar=1285&L2=13&L3=13&srid=27&gp=0

In the “just in time” environment, it is critical that carriers avoid as many delays as possible. Trucks can be delayed by accidents, snarled traffic, bad weather, breakdowns, or even some of the new security procedures being introduced since 9-11. Many of these delays can be minimized or prevented with information. In-cab devices can help provide instant communication and information, including traffic alerts that can be used to help avoid traffic problems in major metropolitan areas. This information can be used to re-route trucks and to alert shippers and receivers of potential delays. When a receiver has advance warning that a truck will be delayed, efforts can be made to have a delivery at the next open window, thus saving downtime for both the carrier and the receiver. Technologies that address internal efficiencies such as route optimization, fuel optimization, driver scheduling, electronic document development, and better integration with shippers’ systems are gaining popularity.

This paper presents the prevailing leading edge technologies that are being offered to and will be available to trucking firms in the near future. We begin, in Section A, with a discussion of the six technologies identified by the American Trucking Associations as the most promising technologies for the industry. Technology is presenting unprecedented opportunities for safety in trucking. Section B presents the current state of safety related technology. Section C discusses advances in truck technology. We conclude with a discussion of technologies that are likely to have a significant impact in the future in Section D. Technology is transforming business practices in the industry. This paper attempts to capture the technological revolution in the trucking industry.

A. Information Technologies in Trucking

The American Trucking Associations identified six technologies that have become critical to success in the trucking industry¹. The technologies that are becoming ubiquitous in the industry are Mobile Communication Systems (MCS), Decision Support Systems (DSS), Automatic Vehicle / Equipment Identification Systems (AVEIS), Electronic Data Interchange (EDI), Bar Coding (BAR), and Imaging Systems (IMG). These technologies have altered business processes and enabled adopting firms to achieve significant improvements in efficiency and productivity. A brief description of each of these technologies is provided, along with some instances of implementation.

A. 1. Mobile Communication Systems (MCS) is an interactive communication tool that links fleet vehicles to dispatch centers. This is essentially achieved by sending positioning information and messages to a central facility that acts as the communication hub between the various dispatch centers and the fleet vehicles. The MCS uses cellular communication technologies, as well as Specialized Mobile Radio Systems (SMRS) and Satellite Communication Systems (SATCOMM). Some common applications of MCS include: position reporting; estimated time of arrival; out of route, a function that provides a warning to the driver and/or dispatcher and records instances when the truck is out of the prescribed route; fuel tax mileage reporting; and decision support systems, to dynamically optimize several parameters such as maximization of contribution per truck per day, driver productivity, etc.

¹ American Trucking Associations (1999). *Understanding the Trucking Industry: Technology in Trucking series*. Alexandria, Va

A. 2. Decision Support Systems (DSS) are computer systems designed to assist decision-makers by synthesizing data to create information and recommendations for action. Most of these systems are interactive, helping employees solve difficult, data-intensive problems. While expert systems and artificial intelligence based systems are becoming more familiar to the trucking firms, operations research based systems are most frequently used. In particular, dispatch operations including routing and the matching of drivers and loads have been gaining in popularity. The advantage of computer based decision support systems can be illustrated with a simple example. A firm with three trucks and three loads to haul faces six different dispatch options. If the firm doubles its size, it faces 720 choices with six trucks and six loads. The number of possible combinations increases into the millions with just 10 trucks and as many loads. Today's load matching and routing software is capable of providing the optimum outcomes given a variety of situations. A DSS allows for the aggregation and analysis of the tremendous flow of real time information that is available to most fleet operators, providing an aid when making business decisions.

A. 3. Automatic Vehicle / Equipment Identification Systems (AVEIS) are communication systems that consist of a transponder programmed with identification, authorization, and any other types of information unique to the user, equipment, or the application. The AVEIS communicates this information using radio signals to a remote reader. There are three common types of transponders which dominate the industry: Type I transponders contain fixed data for read only applications, Type II transponders are capable of read and write operations, Type III transponders provide an external interface with on-board devices or smart cards. AVEIS can be applied to identify:

- Equipment entering or exiting a yard;
- Equipment available within a yard;
- Trucks passing through toll collection lanes;
- Trucks passing through a weigh station;
- Trucks passing through a border checkpoint; and
- Fuel use and authorization.

A common use of AVEIS is in monitoring the status of a fleet of vehicles, including the location and readiness of a vehicle, as well as the overall fleet inventory. This can allow for a significantly reduced fleet size, as well as minimal labor requirements in the tracking of vehicle operations.

A. 4. Electronic Data Interchange (EDI) is a system that provides inter- or intra-company computer-to-computer communication of data. EDI is used to transmit formatted data that would otherwise be maintained and transferred in a printed standard business document such as a freight bill or bill of lading. EDI evolved primarily as a result of eliminating manual paperwork based processes for routine business transactions between companies and enhancing overall productivity by leveraging the speed and timeliness of information exchange between companies. Additionally, EDI based

exchange of business information results in secondary advantages by enabling businesses to plan their work more effectively.

The competing standards in EDI have often required each shipper to have a distinct connection with each carrier. The technology that threatens to replace EDI is the Internet based XML technology. XML (for Extensible Markup Language) is a computer language that is well suited for exchanging electronic documents and for integrating applications running on different operating systems or hardware by using an Internet connection. As the use of the Internet increases, XML is being consistently improved and standardized to encourage widespread adoption.

A. 5. Bar Coding is a system that consists of an automated reader as an alternative to manual (keyboard) entry of data into a database for further processing. Bar code symbols are simply a machine-readable form of keyed data. Scanners use a laser beam of light to read the bar code. Historically bar codes have been used in the motor carrier industry since the 1970s. Over the years, considerable work has been done to standardize bar code placement on bills of lading and freight bills. Additionally, the motor carrier industry has been very active in working with other industry associations to develop common standards for shipping labels. This work has led to benefits across industries and today bar codes in the motor carrier industry are used for a wide variety of applications.

Technological advances in Radio Frequency Identification (RFID) or “smart tags” are threatening to replace barcodes in the near future. These tiny chips send out signals that help monitor shipments in real time unlike barcodes that need to be scanned through a reader. As adoption increases, both in the trucking industry and among the shippers, the cost of the smart tags is likely to decrease rapidly making barcodes increasingly obsolete.

A. 6. Imaging Systems enabling document imaging is an electronic means to store reams of paper. Historically businesses have stored hard copies of documents, requiring enormous amounts of physical space and highly inefficient methods for retrieving and utilizing information. While the advent of microfiche in the 1960s helped cut down the storage space, it did not make a dent in the efficiency category. With electronic storage becoming cheaper and smaller by the day, imaging systems for the use of electronic document management is becoming a business necessity. The functionality of an imaging system is to allow for easy scanning, storage, and retrieval of all business information – trip sheets, bills of lading, fuel receipts, bill payments, proof of delivery, claims, etc.

The use of technology has become widespread in the trucking industry. Firms are using technology to refine processes, cut costs, and increase revenue. However, the technology trajectory has been steep and new technologies and products are being introduced rapidly. New contenders such as XML and RFID are making EDI and bar code technology obsolete. The challenge for trucking organizations has been to distinguish the difference between what technology can do and cannot do. A strong technology base is as important—or sometimes more important—than the ability to move the freight and the choices made in this area could mean the difference between survival and extinction.

B. Technology for truck safety

Each year, trucks are involved in 101,000 crashes that result in injuries. 72% of the trucks on the road today will be involved in serious accidents within the next 5 years. Overall, the trucking industry averages 31,000 accidents a year, or about 2.16 accidents per million miles. The Dept. of Transportation says the average trucking accident leads to \$5,000 in physical damages alone. The Pacific Institute for Research and Evaluation looked at the total cost of the 31,000 truck accidents and 723 truck driver fatalities that occurred in 1997. They came up with a figure of \$24 billion, including \$8.7 billion in productivity losses, \$2.5 billion in resource costs, and quality of life losses valued at \$13.1 billion¹. In order to combat this, new technology is being introduced to warn drivers of imminent problems. Driving simulators, radar systems that alert drivers to upcoming hazardous road conditions and sensors that detect eye closure are some new products that lie in the horizon of truck safety.

B.1. Technology for blind spots detection

The National Highway Traffic Safety Administration (NHTSA) estimated that there were 4,930 fatalities involving large trucks in 2000, the last full year for which figures are available. Of those, an estimated 35 percent occurred because of a collision in one of the blind spots in the feared "no zone" around a truck where a driver cannot see what is happening. A new forward-looking radar system soon to be available to the trucking industry is designed to eliminate truck driver blind spots. The Eagle Eye Object Detection system from Transportation Safety Technologies (TST) is available in two new versions, one for fleets that want a truck or tractor-only system to provide right-side object detection during lane change maneuvers, and a trailer-only version designed to help reduce backing accidents. Studies by Liberty Mutual Insurance and the NHTSA have shown significant accident cost reductions for certain types of accidents by using collision warning or obstacle detection system technologies. Their studies indicate the following accident potential cost-reduction rates:

- 27 percent for rollover/run off the road;
- 52 percent for rear-end accidents;
- 26 percent for interchange accidents; and
- 50 percent for lane-change accidents.²

B.2. Vehicle stability technology

The average cost of a heavy-vehicle rollover is \$120,000, with a yearly, national total cost of \$1.3 billion. That may cover injuries, vehicle and load damage, clean-up, and lost time and productivity for the trucking company, as well as for hundreds, maybe thousands of motorists snared in traffic. Truck manufacturers and their suppliers are working on products to warn drivers of potential vehicle rollover situations. Recently, Meritor WABCO introduced its Roll Stability Control (RSC) system for tractors, and its Roll Stability Support (RSS) system for trailers in order to address this safety issue. RSC is programmed to help prevent rollovers by slowing a tractor when it senses that a critical

¹ Wlazlowski, Tiffany. Technology seen as answer to truck safety problems". Transport Topics. October 2001. Page 14.

² Schulz, John. D. Extra Set of Eyes: New 'Eagle Eye' 360-degree warning coverage designed to make trucker blind spots history. Traffic World. March 18, 2002. Page 21.

lateral-acceleration threshold is exceeded. Intervention comes in three stages: engine power reduction; retarder activation; and service-brake application. RSS is an independent system for trailers and works much like RSC, except a trailer electronically controlled brake system (EBS) and air suspension are required.¹

B.3. Technology to detect driver drowsiness

Studies from Stanford University's Sleep Research Center show that driver fatigue is the leading cause of accidents involving large trucks with drowsy driving being blamed for approximately 31% of the truck related fatalities occurring in 1999. The Government estimates that at least 100,000 crashes, 1,500 deaths, and about \$12 billion in production and property loss can be associated with drowsy driving.² Many companies are using different approaches to develop technology that warns drivers of their level of fatigue and of the performance degradation it causes. Three promising devices are the SafeTrac lane tracker, Perclos eyelid closure monitor, and Actigraph sleep activity monitor.

In large part the success of fatigue management technology will depend upon driver acceptance. If drivers find the machines useful, such devices could help save lives. The driver must also be willing to use the information he receives from them. A strong education in the recognition of fatigue and its causes is an absolute necessity. Even more necessary is the driver's willingness to use what he knows to get the sleep he needs. The products provide the information but the driver has to act on it.

B.4. Technology application for National Security

Since September 11, 2001, homeland security has become an overwhelming concern for the government and trucking firms. Technology is starting to help in the homeland security effort, as well as improving the safety of big trucks. The potential threat to truck drivers, especially those with hazardous loads, is obviously immense, and once a truck leaves its terminal, its only safeguard is generally a lone driver. Some trucks are equipped with high-tech protection, like password access that would make hijacking or theft much more difficult. A truck may require a "driver password" to be keyed into the onboard computer, without which it will shut down. Also, a hijacked driver being forced to comply can input a "theft code" that immediately advises company headquarters. Approximately 125,000 trucks carrying hazardous materials in the United States have some type of tracking and communications capability on board. Through these systems, location, content, and status information are routinely provided to shippers, carriers, and authorized third parties³.

C. Technology for the truck

The pollution created by the trucking industry has long been a source of concern for the federal government and the public. Recently, the Environmental Protection Agency (EPA) has mandated stringent emission standards for diesel engines in trucks. Further,

¹ Richards, Paul. Vehicle Stability on a roll. Commercial Carrier Journal. January 2003. Available at <http://www.etrucker.com/apps/news/article.asp?id=32351>

² Schulz John. D. Safety Galore. TrafficWorld June 26, 2000 Pp 27-28

³ Joey Ledford. High-Tech Systems Work To Keep Big Rigs Secure *Atlanta Journal Constitution* March 5, 2003 available at <http://www.accessatlanta.com/ajc/metro/0303/05ranger.html>

new solutions are being considered as alternatives to the pollution created by idling trucks at truck stops. This section presents the various alternatives on the horizon that manufacturers are presenting to comply with EPA mandates and to reduce truck idling. We also discuss the new opportunities for efficiency and safety created by tire inflation sensors and electronic brake systems. Together, these technologies enhance the driving environment for the trucker, provide safety and operational advantages for the business, and a cleaner environment for the public.

C.1. Diesel engines face challenges

Fleets are facing an interesting challenge when they buy new trucks integrating low-emission engines into their operations. Engines built after October 1, 2002 must meet the EPA's stricter emission standards, bringing a good deal of new technology into the mix. According to the Diesel Technology Forum, engine makers will have to make changes in four areas in order to meet the 2007 standards: cleaner diesel fuel; fuel injection systems; air intake management and exhaust gas recirculation (EGR); and after treatment technology. Most of the engine manufacturers are using what's called cooled-EGR to achieve lower emissions. Although cooled-EGR engines do have drawbacks, the most prominent being a 3% to 6% reduction in fuel economy, by and large they provide drivers with better performance and responsiveness. So far, it does appear that the technology solutions delivered by the engine manufacturers for 2002 have been successful. They have a higher hurdle in the 2007 mandates.

C.2. Technology alternative to engine idling

The deafening hum and illuminated running lights are the mainstays of the nights at most truck stops. Truck drivers idle their engines primarily to heat/cool the cab or sleeper, and keep the fuel and engine warm in the winter so that it is easier to start. In addition, truck drivers today need to power modern devices, especially computers -- not just to contact home, but also to keep track of inventory, trip planning, and routes. The need for power has increased as the technology on the truck has increased. According to the U.S. Department of Energy, long haul trucks idling overnight consume more than 838 million gallons of fuel annually.¹ The average long-haul truck idles away up to \$1,790 in profits each year².

While several companies offer anti-idling bonuses, fuel-efficient alternatives are emerging through advances in technology. Thermal storage devices for heating and cooling and auxiliary power units for heating, cooling and electrical power are two options. Another proposed solution has involved truck stops where truckers gather to avail themselves of some needed rest. Truck stop electrification has gained momentum through advances in technology that permit lower costs and the potential for widespread availability. For hourly fees starting at a little over a dollar, drivers are able to access specially designed modules offering electrical hookups, ducts for heat and air-conditioning, and connections for cable television, phone and computer services.

¹ Vise, Avery. Money for Nothing. Commercial Carrier Journal. March 2003. Available at <http://www.etrucker.com/apps/news/article.asp?id=34989>

² www.ipd.anl.gov/ttrdc/idling.html

C.3. Tire inflation sensor technology

The tires on the tractor and trailer are often the carriers' largest maintenance cost, and proper inflation is considered essential to getting the most life out of truck tires. Keeping tire pressures within tolerances is one of the most vexing jobs in maintenance. A study done for the Federal Motor Carrier Safety Administration claims that truck fleet managers may be making a costly mistake in their reluctance to purchase tire pressure monitors and automatic inflation systems in large numbers. The average truck fleet loses \$750 per tractor-trailer combination every year because of under-inflated tires, according to data collected for the study.¹

First generation solutions include sensors attached to the tire or strapped to the wheel rim enabling fleets to read air pressure and tire temperature with hand-held or drive-by short-range radio receivers. Onboard inflation systems constantly monitor each tire's pressure and keep the tire inflated to the optimum level. The "smart" tire is now on the horizon². Radio frequency identification (RFID) - the same wireless technology that shippers rely on to track movement of their goods - is finding a role in monitoring the condition of truck tires. Several manufacturers are placing computer chips on individual tires that read and report air pressure and tire temperature.

C.4. Electronic braking systems (EBS)

Traditional brake systems use air signals, which travel at the speed of sound under ideal conditions. Electronic braking signals, however, travel at or near the speed of light, which will permit implementing braking behavior among trucks that is similar to that of a passenger car. The advantages of EBS cover a spectrum ranging from safety performance to drivability to lower maintenance costs. Using special software and a kingpin-mounted sensor, tractor-based EBS can maintain the correct braking relationship between the tractor and trailer. The result is safer brakes that last longer. The braking action is both faster and more consistent, whether or not the vehicle is loaded. Potential benefits of EBS include enhanced tractor-trailer compatibility (eliminating brake imbalance); automatic hill holding (by linking EBS with engine-management systems); blending of engine retarder and service brake actuation (to cut brake wear); incorporation of lining-wear indicators (to rationalize maintenance scheduling); and equalization of lining wear (from left to right on vehicle).³

Technologies that enhance truck performance and reduce pollution are on the horizon. As new products are introduced, the potential pay-off from these technologies will become more evident. The adoption of these technologies offers the potential for firms to trim costs and improve margins. Innovating firms have to satisfy federal regulators including NHTSA and the EPA while creating products that clearly benefit the trucking industry. Through a combination of federal mandates and voluntary adoption, the trucking industry

¹ Johnson, Jeff. Study urges adoption of tire technology. *Transport Topics*. Feb 10, 2003, Iss. 3523; pg. S1-2.

² Ryder, Andrew. Dial up signals from sensors to see what your tires are doing. *Transport Topics*. Feb 10, 2003, Iss. 3523; pg. S1- 5.

³ Cullen, David. Smart brakes Fleet Owner. Overland Park: August 1999 Vol. 94, Iss. 8; pg. 58-62.

is headed toward shaping a cleaner, safer, and more efficient environment for the drivers, the business, and the general public.

D. Technology in Trucking – 21st century applications

The previous sections have presented the current state of the art in trucking technology. The editors of Commercial Carrier Journal, in a recent issue, presented their thoughts on technological applications that are likely to influence the trucking industry the most in the next decades. Many of the topics discussed earlier are on this technology frontier. These technologies are likely to significantly affect the productivity and safety of trucking firms as the trajectories advance and the products diffuse throughout the industry. Below are some other examples of technological applications that are likely to further advance the trucking industry.¹

Weight on the go

Onboard weighing devices will become more widely adopted. For example, in one version of such a system, a microprocessor taps into suspension air pressure to determine and display ground weight, to within a couple of hundred pounds. These systems can reduce or eliminate commercial scale fees, as well as the costs associated with out-of-route miles to drive to weighing scales and overweight fines.

Electronic flue-injection/serial data link

The electronic control unit (ECU) uses input from sensors monitoring accelerator pedal position, engine and road speeds, and a host of other parameters to calculate the on and off signals of proper duration. These signals are then sent to electromechanical injectors to precisely regulate the amount of fuel for given operating conditions. The ECU and the “language” it speaks will open a wide range of possible intra-vehicle communications-based applications.

Multiplexing

Multiplexing is a system of sending multiple, simultaneous control signals to various devices, along a single wire. For example, consider a driver that switches on his/her left-turn signal. The turn signal is a smart device that sends a coded message to the flasher, along the same wire that is used to signal all other electrical devices on the truck. The flasher, itself a smart device, recognizes the one signal and ignores all others. It then “knows” to send a message to the left turn lights. The smart lights recognize their unique signal and start flashing. All this happens practically instantaneously. This technology has the potential to drastically reduce the wiring requirements inside a truck.

E-training

While hands-on face-to-face training is still the most widely used technique, technicians are constantly looking to supplement this traditional training via computer-based CD-ROM and internet-based training. With electronic training, drivers not only receive on-demand training, but also valuable and marketable computer literacy skills.

¹ See also: Technologies that will advance trucking in the 21st century. Commercial Carrier Journal. January 2000. Pages 34-42.

Conclusion

Advances in information technology, communications, and digital technology have provided the trucking industry with the means to cope with challenges presented by the new competitive environment. Trucking firms continue to struggle to conform to new and upcoming regulations in emissions, ergonomics, and diesel fuel. The operating environments for the driver, the fleet manager, and the firm, are undergoing tremendous shifts as new technologies are offered in all facets of the business process. These technologies are coming faster than fleets can adopt and utilize them. Also, adopting a technology before the fleet and the firm is ready for it can be as detrimental as waiting too long to adopt it. The challenge of the future for the trucking industry is to incorporate technological advances at just the right time so that the benefits from the use of technology can be fully accrued.

The rapid diffusion of technology may be good for economies, but companies derive the greatest advantage from innovations when competitors can not adopt them quickly. After many companies in a sector have implemented a set of IT applications, these applications become just another cost of doing business, not sources of competitive advantage. Competitive advantage arises from technologies that generate new products, processes, and services or substantially extend a company's existing advantages. These advantages are accentuated when technology adoption is accompanied by broader changes in business processes and organizational structure.¹ Technology is presenting new opportunities for excellence in the trucking industry. Survival and success will depend on the rate at which firms initiate and accept the technology driven challenge of the new competitive landscape.

¹ Nagarajan, A.; E. Canessa, W. Mitchell, and C.C. White III. (2001). E-Commerce and competitive change in the trucking industry. In *Tracking a Transformation: E-commerce and the terms of competition in industries*. BRIE – IGCC E-economy project. Washington D.C. :Brookings Institution Press

4.2

Futures for Traditional Industries: Strategic Issues in the Pulp and Paper Industry in Georgia

Charles Estes, Alan Porter, and Alisa Kongthon¹

INTRODUCTION

Today's discussion on the future of manufacturing is concerned primarily with new high-tech industries. However, it is also important not to overlook traditional manufacturing and its prospects and challenges for the future. Georgia has a number of traditional industries present in the state, and has been implementing a unique program geared specifically to traditional manufacturing—Traditional Industries Program (TIP3). The TIP program receives about \$3.4 million a year to fund about 40 research projects annually that address common issues and encourage innovation in pulp and paper, textiles and carpet, and food processing sectors. Case in point – the pulp and paper industry. There are about 550 mills employing 175,000 workers in the U.S. that generate \$100 billion in shipments or 30 percent of global production. In Georgia, pulp and paper accounts for about \$10 billion in annual shipments and 30,000 employees. The U.S. pulp and paper industry faces increasing cost-based competition in a mature, slow growth, high capital intensive environment. More and more of these firms are consolidating to maintain production output and profitability.

TIP3 Steering Committee is currently working to develop a 5-year strategic research plan for the pulp and paper industry. Georgia Tech's Technology Policy and Assessment Center (TPAC) worked with the Committee toward this objective. This report summarizes the three main parts of our study:

1. Profiling of empirical (literature-based) information on worldwide research activities
2. Survey of industry and other knowledgeable persons concerning prospects for the industry in Georgia over the coming decade
3. Suggestions on key factors affecting the industry and attendant research opportunities deriving from four workshops of industry and other knowledgeable persons

RESEARCH PROFILE: PULP & PAPER MANUFACTURING

In July, 2002, we explored pulp & paper manufacturing research using the *Engineering Index (EI Compendex)* database. This database covers engineering-related research papers in journals and conferences. We tried various search algorithms and retrieved

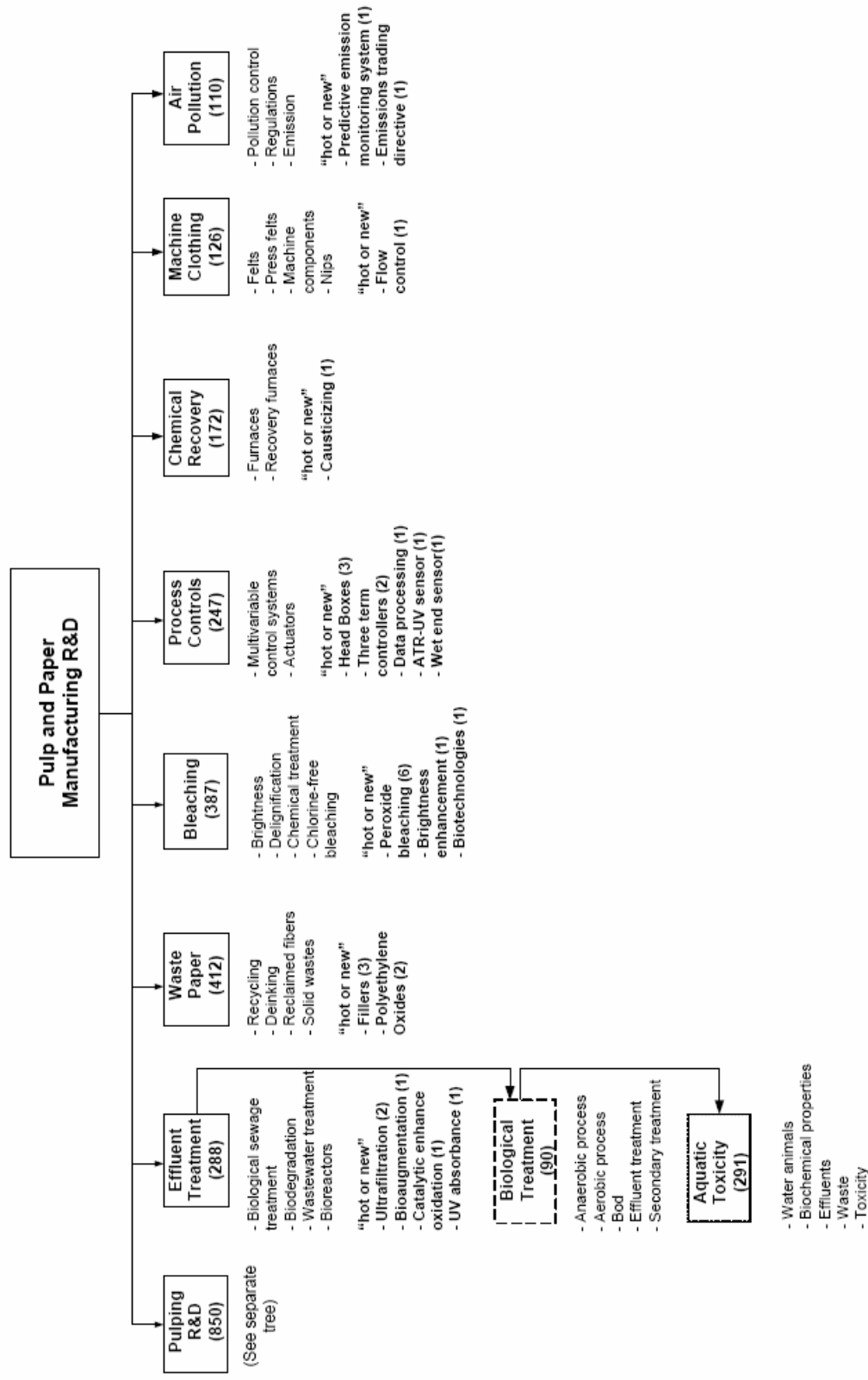
¹ This paper formed the background for a presentation given by Charles Estes, the Program Manager of the Traditional Industries Program at the Economic Development Institute at the Georgia Institute of Technology in Atlanta, GA. The paper was written by Alan Porter and Alisa Kongthon of the Technology Policy & Assessment Center (TPAC) at Georgia Tech.

1835 abstracts. We listed and mapped leading keywords from these papers for expert review to help us determine a wellrounded final search strategy to assure good coverage of related R&D. We also examined "class codes" for another perspective on research coverage. We noted leading journals and the balance of academic and industry-based research. Results can be made available on request.

Based on the preliminary research analyses in *Engineering Index*, we determined to redo our search in the leading industry database -- *PaperChem*. The following charts and notes highlight research activity worldwide based on a search in this database for the period, 1997-2002. That search yielded 2237 abstract records. Figure 1 shows our understanding of major pulp & paper manufacturing research categories. The first category, pulping, is expanded in Figure 2. Note also the "hot and new" topics spotlighted within the categories. These are offered as stimuli to researchers and research managers to determine if any merit further probing.

We note the extensive emphasis on environmental issues. Figure 3 arrays topics as a bar chart showing the percentage of the papers associated with particular leading topics. Figure 4 expands the same bar chart to show highly active sub-topics as well. Figure 5 contrasts Scandinavian and Georgian authors' research emphases. This comparison was suggested to us because of the perspective that Scandinavia is the technology leader in the field. The top portion shows the leading substantive keywords in the respective literatures over the past six years. Scandinavian research appears more active in pulping issues, math modeling, exploration of fiber possibilities, and, to a lesser extent, process control. The bottom part of the chart shows additional leading keywords from Georgia articles. TIP3 may want to consider these current emphases to determine whether they want to initiate activity in under-represented areas, or pursue particularly important research fronts even if these are already heavily treated.

**Figure 1. PULP & PAPER MANUFACTURING RESEARCH PROFILE:
ANALYSES OF RESEARCH LITERATURE (1997-2002)**



Notes:

- This tree is constructed from the factor map of 472 keywords (those occurring 10 or more times, excluding general terms such as paper and pulp mills, papermaking, paper mills, pulp mills, etc.) based on 2,237 journal articles from PaperChem for 1997-2002.
- The main headings in the above trees mostly come from the factor map as the most central keyword of the cluster (except for aquatic toxicity which was suggested by Robert Sackellares.) The number in the parenthesis after each topic represents the number of articles within that factor. For each topic, sub-topics are the high-loading keywords for that Factor (cluster).
- To identify what's "hot or new", we first create a new data subset for each topic, and then create a co-occurrence matrix between keywords and publication years for trend analysis to identify 'hot' topics. We also create two time slices: one for 1997-2000, another for 2001-2002. Then we compare the title phrases between these two groups to identify 'new or unique' topics. The number in the parenthesis after each 'hot or new' topic represents the number of records containing that keyword. Note that the number of records for the year 2002 is quite low since the year is not ended yet.

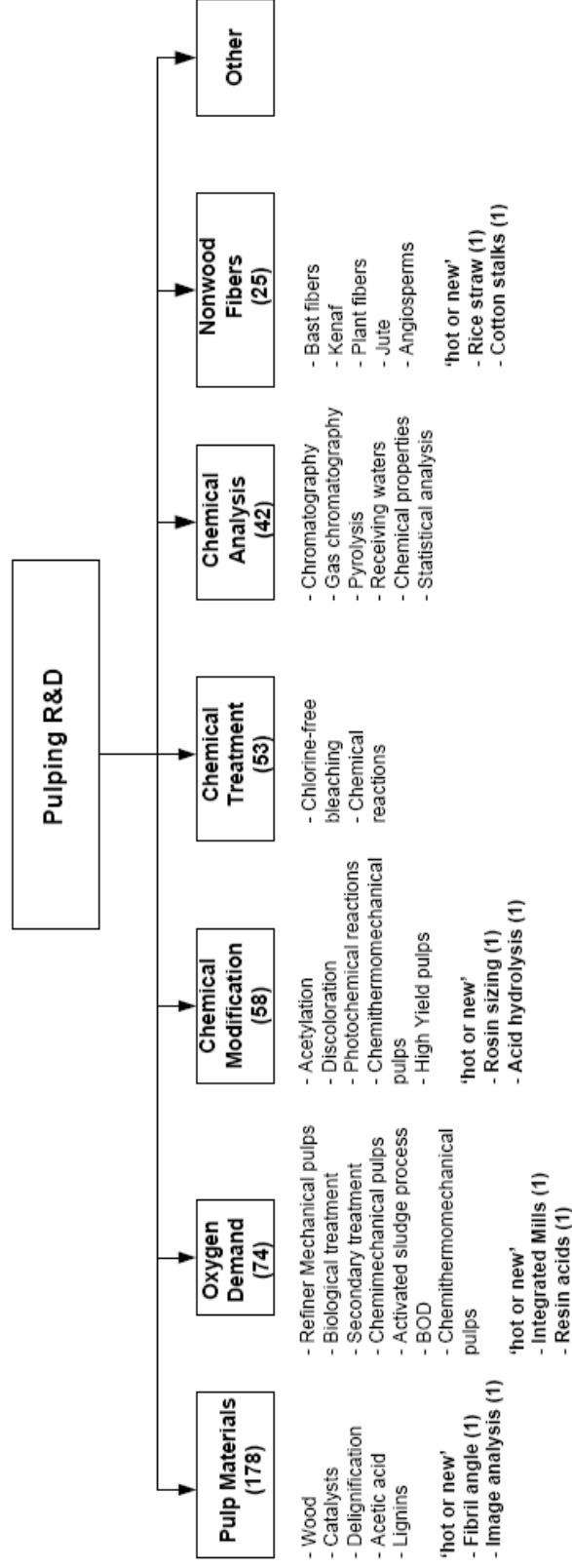
Publication Year	# Records
1997	409
1998	368
1999	358
2000	577
2001	391
2002	134

- A lot of the research seems to focus on environmental issues.
- Some research on process control and instrumentation (i.e., machine clothing)

Definitions

- **Bioaugmentation**- the application of selected microorganisms to enhance the microbial populations of an operating waste treatment facility to improve water quality. (from <http://www.bioaugmentation.com/>)
- **ATR (Attenuated Total Reflection)-UV sensor** - The ATR-UV technique provides simultaneous hydroxide, sulfide, and carbonate analysis with a single scan and eliminates the sample dilution required when conventional UV spectroscopy is used in analysis of kraft white and green liquors. (from <http://www.ipst.edu/>)

Figure 2. "PULPING" RESEARCH PROFILE:
ANALYSES OF RESEARCH LITERATURE (1997-2002)



Notes:

- This tree is constructed from the factor map of 512 keywords (those occurring 4 or more times, excluding general terms such as paper and pulp mills, papermaking, paper mills, pulp mills, etc.) based on 850 journal articles (the new data set which contains the keyword 'pulp,' except 'paper and pulp mill' and 'paper and pulp industry,' extracted from the original 2,237 records).
- 'Hot or new' topics are created the same way as for the 'pulp and paper manufacturing R&D' tree.
- We cannot find 'hot or new' sub-topics for 'Chemical Treatment' and 'Chemical Analysis' topics. The reason could be that there are few records for these two topics. Of the 53 records relating to chemical treatment, there is only 1 record for 2001! There are 42 records for chemical analysis and only 4 records for 2001.

Figure 3. PROMINENT PULP & PAPER MANUFACTURING RESEARCH TOPICS

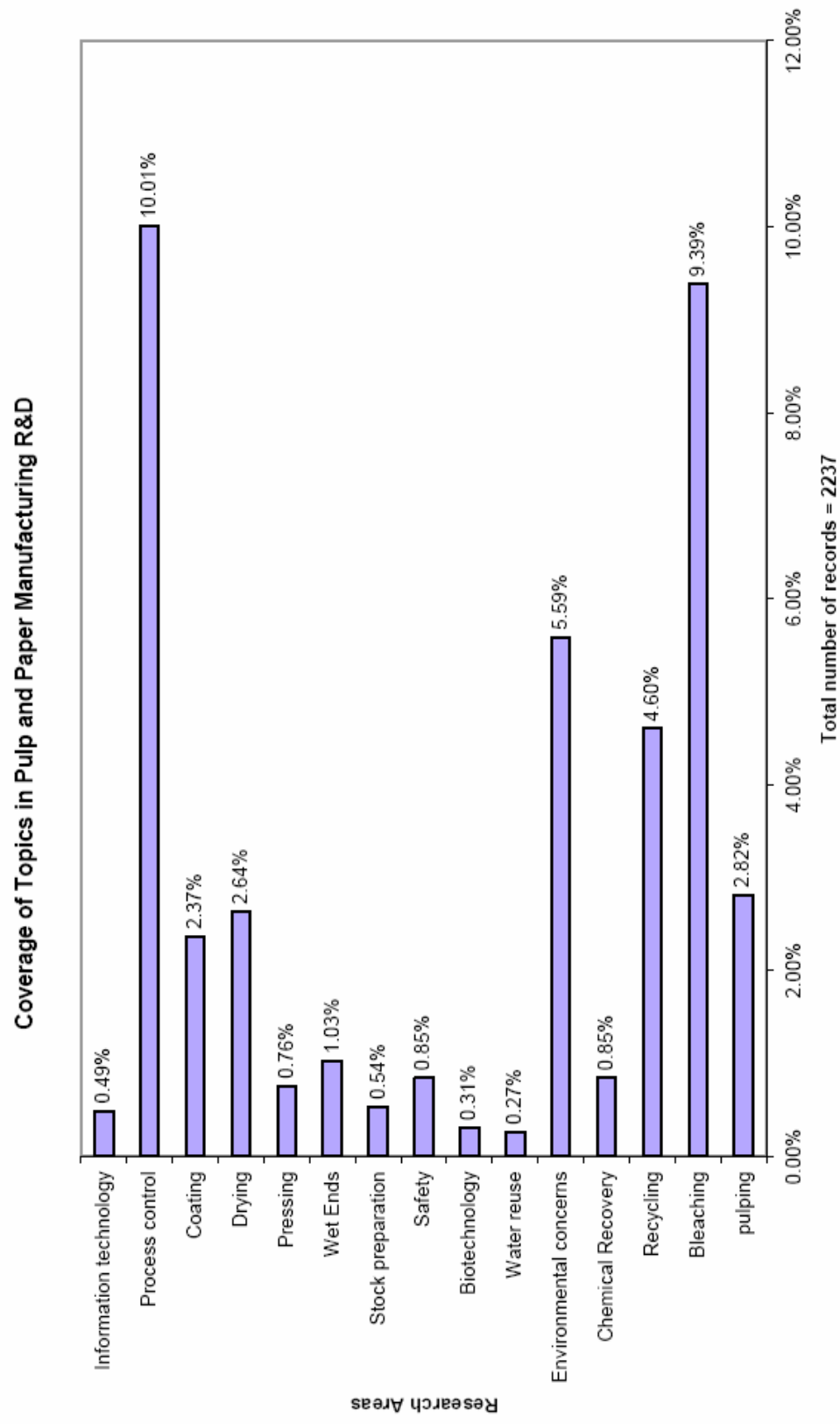
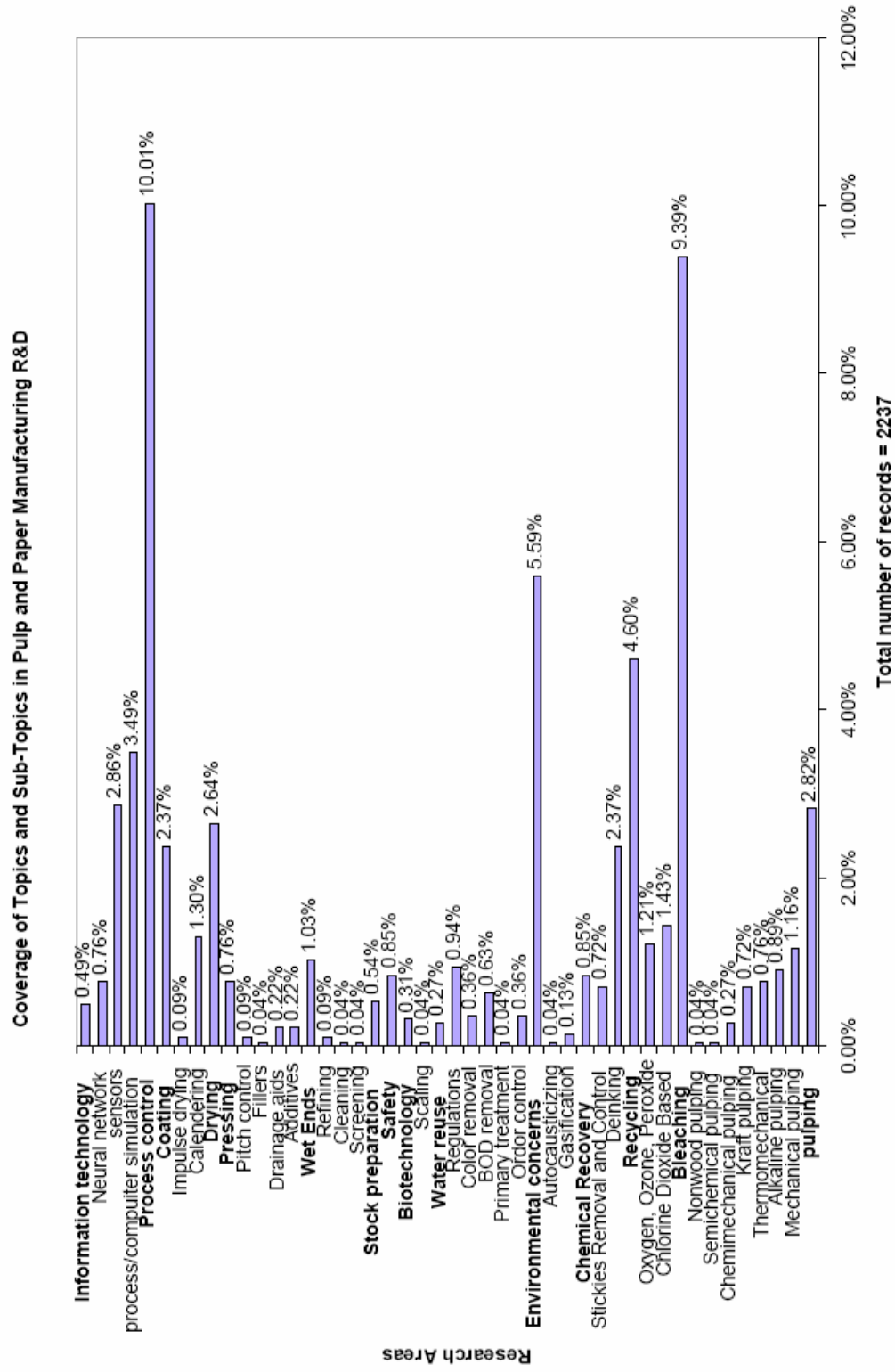


Figure 4. PROMINENT PULP & PAPER MANUFACTURING RESEARCH TOPICS and SUB-TOPICS

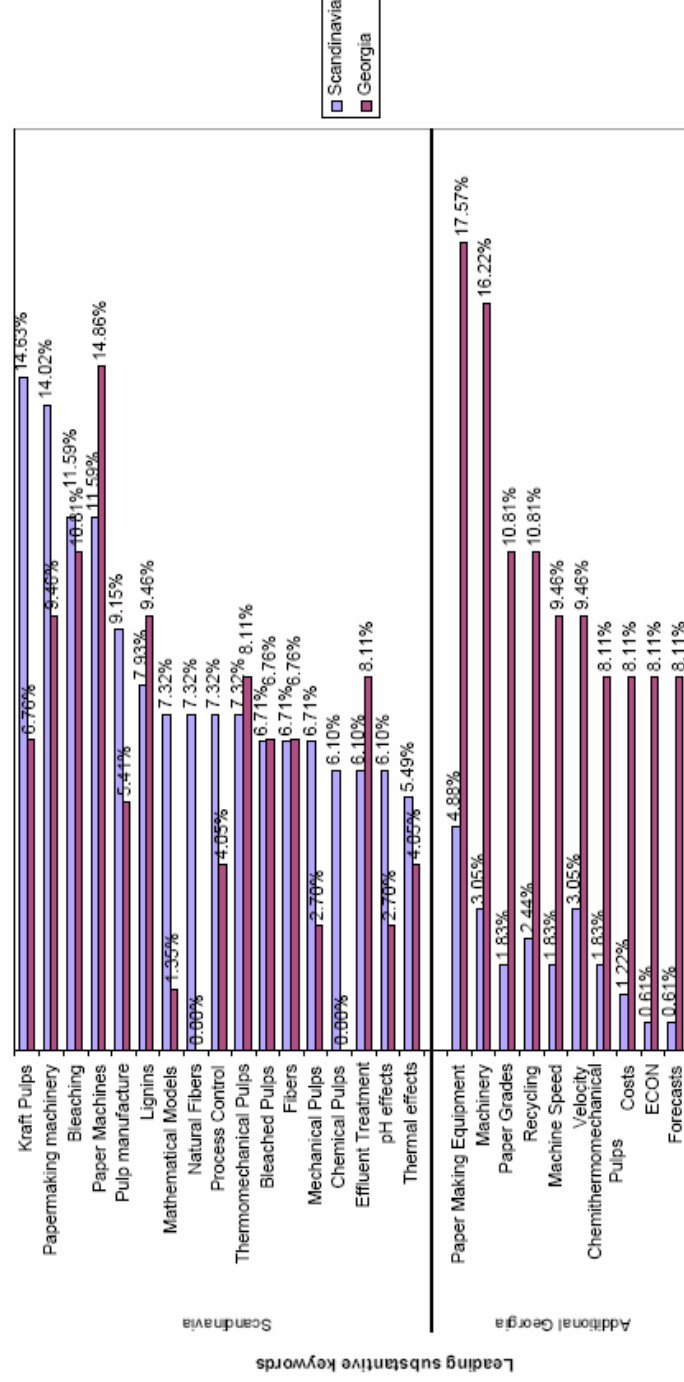


Notes:

- These two charts are created using the categories of technologies and related topics research provided by Tom McDonough.
- Coverage is the percentage of records containing the topic as their keyword.
- The above charts indicate that there is more coverage on process control and bleaching than environmental concerns. This is different from our findings from the factor analysis which indicate that much of the research focus lies on environmental issues. The reason for this difference could be that the bar chart is constructed by only counting records whose keyword is the same as the topic, while the results from factor analysis are concepts created by grouping keywords.

Figure 5. SCANDINAVIAN vs. GEORGIAN RESEARCH TOPICS

Comparison between leading substantive keywords of Scandinavia and Georgia



Total number of records of Scandinavia = 164, Total number of records of Georgia = 74

Notes:

- The top section of the plot includes the leading substantive keywords of Scandinavian authored articles. The bottom part contains additional leading substantive keywords from Georgia articles. Note that some Georgian emphases coincide with Scandinavian ones.
- Scandinavian research is notably more active in pulping issues, mathematical modeling, natural fibers, and (to some extent) process control.

TIP3 SURVEY

We determined to conduct an e-mail survey of knowledgeable industry and other professionals concerning certain major issues confronting Pulp & Paper Manufacturing. With the help of Charles Estes, Tom McDonough, and TIP3 Steering Committee members, we identified candidates for the survey. We also asked respondents to suggest others. In all, we received 31 responses.

Our respondents can be categorized as follows:

* **University/Industry Research Organizations:** 14

[IPST -6, CPBIS -2, Herty -3, UGA -1, Georgia Tech -2]

* **Industry:** 12

[Georgia Pacific -4, Weyerhaeuser -2, Other P&P Co.'s - 4, TAPPI -1, rtd -1]

* **Other Perspectives:** 5

[GT-Econ Dev Inst -2, Savannah Econ Dev -1, GA Forestry -1, Southern Co. -1]

Within industry, we sought a variety of points of view -- planning and research, environmental, mill management, etc. However, we don't have positions well-identified. Our response numbers do not seem large enough to warrant trying to separate responses by category. Response profiles on each of the questions posed appear as Appendix A. Table 1, just below, summarizes these by showing the average (mean) responses. [Respondents were to provide a percentage estimate, summing to 100%, on the options within a given issue.] The message is clear -- Georgia pulp & paper manufacturing confronts a strikingly **uncertain** decade ahead. Responses reflect almost maximum uncertainty. Will environmental considerations tighten to mandate radical process changes? Half expect so; half expect not. Will the economic climate stay the same, brighten, or worsen? Half expect about the same; a quarter, brighter; a quarter, gloomier. Will process technology radically change? Two-thirds think not over the next 10 years; one-third think so. Will Georgia's pulp & paper product mix change? Half expect no major change; half expect that new products will make a big mark.

Table 1. PERSPECTIVES ON KEY INDUSTRY ISSUES FOR THE COMING DECADE

■ Environmental Concerns & Regulations	
* new ones arise that mandate radical change to pulp or paper processes	48%
* no more stringent than today	52%
■ Economic Climate for the Industry	
* much as today	48%
* brighter	27%
* gloomier	25%
■ Process Technology	
* much as today	64%
* radical advances	36%
■ Demand for New Products	
* GA mix similar to today	54%
* New products offer significant commercial opportunities beginning by 2010	46%

SCENARIO SIMULATION WORKSHOPS

Based on the survey results showing marked uncertainty as to key facets of the industry over the coming decade, we decided to invite experts to gauge which factors and research opportunities appear most important using a "what if" approach. We devised a "scenario simulation" approach based on a method developed by The Futures Group under Ted Gordon. It has been applied in various arenas (e.g., helping the Gas Research Institute assess its research priorities). In essence, we conformed 4 workshops, each focusing on a given set of assumptions concerning the 10-year future for Georgia's pulp and paper manufacturing. Participants were asked to "buy in" to one scenario for their workshop, and accordingly identify key forces and factors affecting the industry's future prospects. We then sought to focus on the leading forces and factors for the coming 10 years, and specify research priorities for the next 5 years. The process is a version of the Nominal Group Approach (NGP) in which individuals are first asked to jot down ideas; then we go around the room requesting one idea from each person. That is followed by open discussion (brainstorming) and a voting procedure to sort out the most promising of the ideas generated.

The four scenarios were:

1. The Rolling Stone -- incremental change from the present
2. Waterworld -- water pressures severe
3. The Landfill Is Closed -- recycling "everything" emphasis coming from Europe
4. Viking Invasion -- innovative competitive fiber-based products invade from Europe

The brief scenario write-ups and session instructions appear as Appendix B. In most of the workshops we had time to refine the Second Charge to ask specifically for suggestions for TIP3 to pursue.

We conducted four workshops -- Dec. 3, Jan. 10, Jan. 16, and Jan. 17. Jan. 16 was in Savannah and the other three were in Atlanta at IPST. Of the 31 survey respondents, 26 participated. Another approximately 11 persons joined, with one participating in two workshops. These included 4 with Pulp & Paper Company backgrounds, 3 from government, two from universities, and one from Georgia Power. So the mix of backgrounds is similar in the survey and the workshops. Charles Estes participated in all sessions. So, the total number engaged was about 37 persons, with an average of 10 per session. Participation in each session ranged from about 6 to 12 persons, not counting the moderator (Alan Porter) and recorder (Alisa Kongthon).

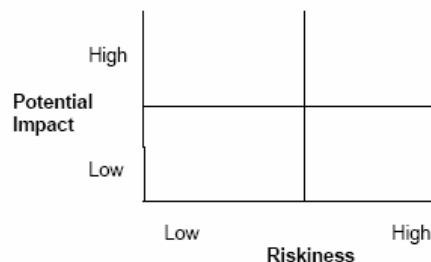
Each workshop generated long lists of notable influences acting on the industry and of candidate research topics. These appear as Appendix C. We heartily recommend that researchers and research managers browse these raw lists for ideas to consider. Our intent was to review the research topics nominated to see which appear as priorities under multiple scenarios. In other words, given the extremely high uncertainty confronting the industry, TIP3 would seem well-advised to select research projects likely to yield high payoff under various conditions.

CANDIDATE RESEARCH PRIORITIES

Discussion at the TIP3 Steering Committee meeting (Jan. 21) brought forth the notion of considering research possibilities along two dimensions. Figure 6 offers a schematic to help prioritize promising research areas. Obviously, topics with low risk and high potential impact are extremely attractive. But, so may be high risk/high potential and low risk/low potential projects. These dimensions appear to track well with the distinction between:

- long term/fundamental research (potentially high impact with high risk of not being utilized by Georgia's industry anytime soon), and
- short term/applied research (potentially fast payoff by helping Georgia mills "survive" and prosper).

Figure 6. A TWO-DIMENSIONAL MATRIX TO HELP SORT RESEARCH AREAS



We have sorted the nominated research topics. Table 2 consolidates selected leading topics by scenario in which they were noted. Observations follow the table.

Table 2. RESEARCH TOPICS FOR THE FOUR SCENARIOS

The Landfill Is Closed	Viking Invasion	The Rolling Stone	The Waterworld
New product and market development	High value replacement/ new products	New product development	Product innovation
Flexible processes for environmental challenges	Environmental factors - recycling	Environmental issues - water reuse and recycling, zero odor pulp mill	
Consumer relationship understand consumer demand, ties to fiber demand, products, links into manufacturing processing and regulatory issues	Work with customer to define future product needs		
		Fiber issues: 1) Creating plantation to grow hardwood fiber alternatives 2) research for recycle fiber to equal virgin fiber	Fiber issues: 1) Fiber engineer (e.g., modification of So. Pine fiber); 2) use of fiber (new materials, composite)
		External issues: use/reuse of water, odor, color, air	External issues: odor, foam, color
Transportation, logistics and infrastructure to pickup/delivery recycle product to the mill			
Gasification of solid waste	Energy use and production	Bio fuel (black liquor, crop residues)	
Life cycle analysis			Life cycle analysis
		Differentiate products (vs. commodities)	Differentiate products (from commodities)
Sludge products - technology for volume, absorbent product, agriculture (biodegraded), development of alternative products			
	Reduce process cost		
		Softwood issue: using cellulose as polymer	
			Public policy "table setting" - re: employment, education, business competitiveness for both national and international level

	Competitive advantage - best management practices, communication		GA mill - adaptable projects, aware of current status, best practice
		Develop industry synergies (Food industry + carpet waste+...)	
		"Mill of 2025"	

Observations on Table 2:

1. Note that not all items in any row relate. Presentation seeks to be concise.
2. Common research topics across our scenarios are new product development and innovation, environmental issues, fiber issues, life cycle analysis, consumer relationship, external issues (e.g., odor, air, color), and differentiating products (getting away from commodities).
3. Environmental issues are important research topics. This agrees with our pulp and paper R&D publications profile.
4. Research topics seem to be divided into two categories: industry technical issues and public policy issues
 - a. Industry technical issues such as new product development, cost structure (e.g., how to reduce capital and operational cost), intellectual capital capture.
 - b. Public policy issues regarding employment, education, business competitiveness for both national and international level, regulatory/tax
5. 4 key factors for pulp and paper manufacturing are water use, operations/processes, product competitiveness, and fiber supply.
6. Only one group suggests research on replacing recover boilers with gasification because energy consumed will decrease, environmental benefits will increase, and yield will increase. This seems to be a very important research.
7. Short-term vs. long-term payoff
 - a. Short-term: 5 to 10 years can be too short to develop new processes. For short-term payoff, we could think of product development not fundamental process change.
 - b. Long-term: mill of the future "mill of 2025" with following characteristics: efficient products, mini mill using recycle fibers, use of agriculture waste fiber, different processes, zero use of water from community (closed loop), research on water purification (using cellulose), lower labor cost, environment and public relation gains, zero odor, portable (e.g., on the ship)
8. GA has infrastructure in place: we have recovery boilers, educated workforce, research center, fiber (virgin and recovered), water supply, ports, cheap energy but what's holding GA back? Could it be the decrease in technical workforce and research staff, lack of innovative research, foreign competition (e.g., China has cheaper labor, Scandinavian countries are more innovative and have better workforce training)?

10. To promote R&D in this area, we can broadcast research and results to the media, and show how they can benefit GA economy. Also we can outreach to the academic community through TAPPI.

How can Georgia best position this industry to exploit new opportunities? We offer our perspective on particularly "interesting" research ideas. Table 3 consolidates these. We were struck by how many suggestions entailed multiple, interacting aspects -- i.e., "systems" issues. The second bullet arose from the first workshop and has been added as a topic in this year's call for proposals. "Four key factors" was an integrative perspective offered in another workshop. The "Mill of 2025" generated discussion of a range of considerations that could be packaged together as a research theme, if TIP3 decides to address longer range payoff projects. Another appealing idea was to consider funding selected case studies on best practices and dramatic failures.

Table 3. INTERESTING RESEARCH OPTIONS FROM THE WORKSHOPS

-
- Systems Approaches
 - Life Cycle Analysis & Sustainability
 - Fuller utilization (energy, secondary products)
 - Recycling logistics
 - Integrative policy
 - Water: Industry + Agriculture + Urban
 - Addressing factors beyond industry control
 - cross-GA-industry synergies
 - Given GA's strengths, what's holding us back?
 - How to utilize our recovery boiler resources?
 - 4 Key Factors
 - Operations/processes – incremental & radical change
 - Product competitiveness & differentiation (> commodity)
 - Fiber supply & engineering (cellulose as polymer; composites)
 - Water
 - Mill of 2025
 - mini-mills
 - integrated mill modeling
 - Case studies
 - Best practices
 - What went wrong...?
-

4.3

Human Side of Manufacturing Technology: Demographic Changes, Training Needs and Skill Gaps

Cheryl Leggon¹

This paper examines human resource issues in the context of changing manufacturing technology. The first section reviews demographic changes in the United States (U.S.) over the past 50 years, and demographers' projections for the next 20-50 years. The second section discusses the relationships between demographic changes in the U.S., overall, and how they influence the composition of the labor force. The third section reviews changes that have taken place in manufacturing and their impacts on productivity and employment. The final section explores training needs and ways to meet those needs.

Demographic changes in the United States population: 1950-2050

The past decade has been one of significant demographic change in the U.S. For example, during the period between 1990 and 2000, the U.S. experienced the largest numerical increase of any other decade in its history. This is significant because the main determinants of labor force growth are population growth and changes in labor force participation rates. Among the most significant factors are demographic changes in the gender, racial, and ethnic compositions, and the age structure of the U.S. population.

Gender composition. The male-female ratio by race and ethnicity for the U.S. is shown in Figure 4.3.1. This ratio is operationally defined as the number of males per 100 females. Hispanics/Latinos (of any race) have the highest male-female ratio—106 males for every 100 females, followed by Native Hawaiian and other Pacific Islander—101 males for every 100 females. African Americans have the lowest male-female ratio with 91 males for every 100 females.

Race-ethnic composition. Over the past 50 years, the U.S. population has become increasingly diverse. It is noteworthy in general, and significant for manufacturing in particular, that the United States is currently the only industrialized nation with rapid population growth due primarily to immigration (Population Resource Center). Most recently, these immigrants are primarily Hispanic and Asian, are younger, and have higher labor force participation rates than the rest of the U.S. population.

Between 1990 and 2000 the Hispanic population² grew by almost 58 percent, from nine to 12.5 percent of the U.S. population. During that same period of time the African

¹ Cheryl Leggon is an Associate Professor in the School of Public Policy at the Georgia Institute of Technology in Atlanta, GA.

² "Hispanic" is an umbrella term that groups people with different national and historical origins. This is unfortunate, insofar as a dip skews significant differences between populations. Nevertheless, the U.S. senses uses "Hispanic" to refer to people descended primarily from Mexico, Central America, and South

American¹ population grew almost sixteen percent to comprise 12.3 percent of the U.S. population. The Asian population² grew 32 percent and made up almost four percent of the total U.S. population. Again the growth in both the Hispanic and Asian populations is largely due to immigration.

Age structure. The labor force is affected not only by changes in the race/ethnic composition but also by changes in the age structure. As the baby boomers (those born between 1946 and 1964) age, older age cohorts are expected to make up a larger proportion of the labor force in the next two decades. Moreover, the baby boomers are likely to stay in the labor force longer and retire later than previous cohorts for a variety of reasons. First, as a cohort, the baby boomers had children later than previous cohorts (and may be still paying to educate them). Second, given the increased life span, many baby boomers are caring for children as well as aging parents. Third, economic issues—such as unexpected problems with pension funds—make it necessary for baby boomers to stay in the labor force longer. Therefore, it is no surprise that the U.S. Census Bureau projects that the 55-and-older group, which comprised 13 percent of the labor force in 2000, will increase to 20 percent by 2020 (Toossi, 2002). The U.S. Census Bureau projects that 42 million people will be into the labor force between 1998 and 2008. The people who stay in the labor force are 40 percent white male, 47 percent female, and 25 percent minority. However, the new workers will be 30 percent white male, almost half—50 percent—female, and 41 percent minority. These changes in the demographic compositions of the U.S. labor force for 2000 and 2008 (projected) are shown in Figure 4.3.1. In the year 2025, 40 percent of the workforce will be age 45 and over, as compared to 33 percent in the year 1998. In sum, this means that the U.S. population will age.

Labor force participation: retrospectives and projections.

Between 1950 and 2000, the annual rate of growth for the U.S. labor force was 1.6 percent; the projected annual growth rate between 2000 and 2050 is 0.6 percent. Between 1960 and 1970, population growth accounted for approximately 94 percent of the growth in the U.S. labor force. However, between 1970 and 1980, 76 percent of the labor force growth was the result of population growth, and the remainder was due to the growth of participation rates—mainly of women. The projected annual growth rate between 2000 and 2050 is 0.6 percent.

Historically in the U.S., the number of men in the labor force has been greater than the number of women, although the growth rate of women in the labor force has been significantly higher than that of men (Toossi, 2002). One of the most dramatic changes from 1950-2000 has been the increase in labor force participation of women. Actually, this refers to the increase among white, middle-class women; African American,

America. The two largest groups among this population are Mexican Americans and Puerto Ricans. The first year that data were available on both race and Hispanic origin was 1980.

¹ “African American” refers to people of African descent born and raised in the United States. Often the census refers to this category as “black” period the but this is problematic because this category can also include blacks were not born and raised in the U.S. In the context of human resources in science and technology, this serves to overstate the participation of African Americans in science and technology.

² As is the case with the Hispanic population, “Asian” is an umbrella term that refers to many groups with different national and socio-cultural origins.

immigrant, and poor white women have historically been a part of the labor force. The women's labor force participation rate was 34 percent in 1950 and increased to 60 percent by 2000. This dramatic increase was the result of several factors: major economic expansion after World War II; higher standards of living; and rapid acceleration in the growth of college enrollments.¹ The post-war economic expansion greatly increased the demand for labor. The difference in labor force participation rates for women and men in the U.S. steadily decreased between 1950 and 2000.

The portion of the labor force that is white non-Hispanic has been declining during the past two decades. The portion of the labor force that is white non-Hispanic was 82 percent in 1980, decreased to 73 percent in 2000. Moreover, this decline is expected to continue over the next 50 years. This is due in part to the retirement of the baby boomers; this cohort has a large share of white non-Hispanic men.

The labor force participation rate of African Americans is expected to continue. This is due primarily to two factors: the higher fertility rates among African American women; and the relatively high labor force participation rates of African American women. The share of Hispanics in the labor force was 6 percent in 1980 and increased to 11 percent in 2000; by 2010 it is projected to be 13 percent. Demographers attribute this increase to two factors: immigration; and higher-than-average fertility rates. Asians have been the fastest-growing sector of the U.S. labor force in the past and are projected to remain so for the next half century. Their labor force share more than doubled between 1980 and 2000 from 2 percent to 5 percent, respectively. By 2050, that share is projected to more than double again to 11 percent. The differences in the labor force participation rate by race and Hispanic origin are usually not as big as those among different age and sex groups (Toossi, 2002:23).

Impacts of Changes in Manufacturing Technology on Productivity and Employment

Projections indicate that by 2010, service industries will provide the greatest number of new jobs in the United States. This is due to both demographic and technological factors. For example, as the baby boomers age, there will continue to be a greater demand for specialized services and goods, such as geriatric physicians and social workers and drugs to treat chronic medical conditions, enhance the quality of life, and slow down—if not reverse—the effects of aging. Still another impact of an aging national population is in the creation of new jobs. In 2000, 14 percent of jobs were in manufacturing. Between the years 2000 and 2010, 24 percent of all new manufacturing jobs will be due to new growth, while almost 75 percent will be due to net replacement (*Occupational Outlook Quarterly*, winter 2001-02, p. 12).

Changes in technology can have three outcomes: no change at all; the elimination of some jobs; and the creation of new jobs. In many cases, innovative technology does not affecting the labor force. For example, warehouse managers have incorporated both real-time inventory practices and electronic tracking into their job. In other cases, “increasingly sophisticated automation and robotics have led to new types of silicon and

¹ It is important to note, however, that the major cause of the significant increase in college enrollment was due to the G.I. Bill which benefited males primarily.

biological chipmaking technicians” (Crosby, 2002:17). However, it is important to note that occupations that center on a new technology can become obsolete as other workers learn to use that technology and integrate it into their existing occupations. Still in other cases technology changes do eliminate some jobs. It is difficult to determine if technological change will lead to new occupations (Crosby, 2002). For example, although “nanomanufacturing” could revolutionize how products are developed, it is too soon to tell whether this will lead to the creation of some jobs and the elimination of others. Nevertheless, projections can be made in terms of existing jobs.

Manufacturing is the dominant goods-producing industry. Projections indicate that “real output among industries is expected to expand by nearly \$6.1 trillion” (Berman, 2001:39), as companies continue to capitalize on technological advances to enhance productivity. Comparisons between the average annual rate of change for both employment and productivity for selected industries are presented in Table 1.

Table 1: Average annual rate of change by industry: 1990-2010

Industry	Employment Average annual rate of change		Output Average annual rate of change	
	1990-2000	2000-2010	1990-2000	2000-2010
Manufacturing	-0.3	0.3	4.3	3.2
Durable manufacturing	0.0	0.6	6.5	4.0
Nondurable	-0.8	-0.1	1.7	1.9
Electronic & other electric equipment	0.3	0.6	14.3	5.3
Electronic components & accessories	1.6	1.6	29.3	7.0
Apparel & other textile products	-4.8	-1.8	0.3	2.6
Textiles	-2.7	-0.6	1.3	1.0
Chemicals & allied products	-0.5	0.4	1.8	3.3
Plastics & synthetics	-1.5	-1.7	2.8	4.0
Paper & allied products	-0.6	-0.5	1.2	1.5

Source: “Industry output and employment projections to 2010” by Jay Berman, *Monthly Labor Review*, November 2001, Table 3: Employment & output by industry, 1990, 2000, and projected 2010.

Table 2 presents a list of selected industries, how technology has impacted them, and employment projections for them. Industries producing apparel and other textile products have been impacted the most in terms of losing 103,000 jobs resulting from outsourcing inventory and distribution functions to their party warehouses. Three out of five jobs in the textiles industry are production jobs.

Table 2: Employment Projections by Industry 2000-2010

Industry	Employment Projections	Technology affecting Industry
Apparel & other textile products	16% decline (vs. 16% increase for all industries) Lose 103,000 jobs	Outsourcing inventory & distribution Functions to third party warehouses
Textiles (production workers = 3 of 5 jobs)	Decline by 5.4%	Scientific advancements in - chemistry - engineering - materials science
Electronic equipment manufacturing [disk drives; computer peripherals; ATMs; chips; integrated circuits]	Grow about 7% Professional & related occupations: job growth will outpace over industry Production workers: grow more slowly than the industry workforce [n.b., production workers account for much lower proportion of all workers]	Increasing automation of search & navigation equipment
Electrical & electronic engineers	Grow about as fast as average (16%)	Electrical & electronic goods, including defense-related electronic equipment
Chemical manufacturing (used as intermediate products for other goods) Consists of 8 segments, of which largest employer is plastics, materials & synthetics industry Employs: 4% of total in manufacturing; 10% of those employed in nondurable goods manufacturing	Decline by 4% 50% of all jobs held by production, installers, maintenance & repair workers Growth: agricultural chemicals and paints & allied products Biggest job losses: plastics & synthetics	More efficient production processes & technologies - growing application of computerized controls in standard products - increase in manufacturing specialty chemicals requiring precise computer-controlled production methods → reduce need for workers to monitor or directly operate equipment
Steel	Employment expected to decline by 22% from 2000-2010 Employment declined in 2000 to less than half its 1980 level Best opportunities are for adaptable individuals with technical skills & training in complex manufacturing processes Flexibility: workers are trained to perform a variety of tasks & provide more flexibility to the firm as company's needs change	Increased use of labor-saving technologies & machinery Most strenuous tasks were the first to be automated

Source: *The 2002-03 Career Guide to Industries*, Bureau of Labor Statistics, U.S. Department of Labor.

Projections indicate that scientific advancements in chemistry, engineering, and materials science will result in a 5 percent decline in employment among textile production workers. Increasing automation of search and navigation equipment will result in projected employment growth of about 7 percent overall among workers in electronic equipment manufacturing. These workers make disk drives, computer peripherals, ATMs, chips, and integrated circuits. The professional and related occupations in this industry are projected to grow faster than production workers (who account for a much lower proportion of all workers in the industry).

Among electrical and electronic engineers, employment is projected to grow about 16 percent. This growth is due to increased demand for electrical and electronic goods, including defense-related electronic equipment. Chemical manufacturing employs approximately 4 percent of workers in manufacturing. More efficient production processes and technologies are projected to result in a 4 percent decline in employment. The greatest number of jobs will be lost in plastics and synthetics. An increase in manufacturing specialty chemicals that require precise computer-controlled production methods will reduce the need for workers to monitor or directly operate equipment.

Finally, employment in the steel industry is expected to decline by 22 percent from 2000-2010. Employment declined in 2000 to less than half its level of 1980. In this industry, the increased use of labor-saving technologies and machinery meant that the most strenuous tasks were the first to be automated. The best opportunities in this industry are for adaptable individuals with technical skills and training in complex manufacturing processes. Workers must be flexible in order to be trained to perform a variety of tasks and provide more flexibility as the company's needs change.

The manufacturing work force in the United States during the 1950s, 1960s, and early 1970s largely consisted of people with a high school education. This was sufficient for the manufacturing machinery and processes prevalent at that time. Moreover, some would argue that the quality of a public high school education was higher then than it is now. Now, however, increasingly complex machinery and processes require specialized training. Some sociologists contend that the public school system in the United States—which has been in place since the early 1900s, is no longer adequate to educate and trains people to adequately perform the jobs of today and tomorrow. This public education—grades kindergarten through twelfth—was structured to inculcate in students such traits as obedience to authority and punctuality. These traits were essential to manufacturing workers. However, the U.S. economy is no longer based on the manufacture of durable and non-durable goods; it is now based on the collection, organization, analysis, and dissemination of information. It is driven by technological innovation and requires qualitatively different kinds of workers than were required by manufacturing. Therefore, the public school system must adjust to educate and train the workers for the post-industrial or knowledge economy. This requires restructuring.

Assessing what constitutes an “adequate” human resource base in the context of the future constitutes an exercise in what is often called futures thinking. In the context of this workshop, the futures thinking exercise would be to create scenarios about U.S.

manufacturing capability in the future, and then to identify what education, skills training, and experience future U.S. manufacturing workers would need under each scenario. For example, in one such scenario smart or super-smart machines increase exponentially the productivity of each worker. This would result in the demand for fewer—and presumably workers with more specialized training—than is the case for the manufacturing workforce of the present. Perhaps, it would be both efficient and effective to develop an ongoing relationship with community colleges and vocational schools to retrain workers whose jobs are eliminated by technological innovations.

Future Training Needs

It seems difficult—if not impossible—to answer questions about the impact on human resources stemming from technological changes in manufacturing that have not yet been taken place. Forecasts may overestimate the impact of some technological changes and underestimate the impact of others. However, this is not unique to the manufacturing workforce. In the context of the science and engineering work force, while a person is going through the process of education and training, the jobs that they may eventually hold do not yet exist. Yet, someone must fill those jobs. Before formal training and education programs are devised and developed, how do we fill these jobs? These are precisely the issues discussed in a report that I wrote for the national academy of engineering, “Fostering Flexibility in the Workplace” (NAS, 1990). What should they do to be prepared to do those jobs? Given that we did not know specifically and precisely what kinds of education and skills would be required, the most effective and efficient way to prepare people is to foster flexibility among the current workforce. This means two things. First, in addition to educating/training people in certain substantive knowledge and skills it is imperative that members of the current workforce be socialized to expect to learn new skills throughout their working life. Second, fostering flexibility means that workers should be able to apply their knowledge, skills and experience to changes in their work environment resulting from changes in manufacturing technology—whatever that technology may be.

It is likely that very specialized training would be required to adapt to developments and changes in technology. In terms of the U.S. manufacturing work force in the future, this raises key questions.

- What skills, education, and training would these workers need?
- Who could provide such training?
- Who should provide that training?

Research indicates that “employers are likely to offer on-the-job training for new specialties to workers with diplomas, degrees, and certificates” and that employers are more likely to train workers who have transferable skills (Crosby 2002:24).

Needs resulting from innovations, require innovative ways to meet those needs. For example, instead of having an in-house training function or even outsourcing training to consultants, distance learning could provide an effective and efficient mechanism to deliver training—especially to organizations with workers in more than one geographic

location. Another example is for manufacturing industries to work with community colleges to ensure that workers have the requisite skills.

The question remains: How do we train today for tomorrow's jobs? A key component to this training is really socializing students and workers to expect to learn and train throughout their life. In addition, we must train today's students to be flexible and adaptable. Specifically, we must teach students to apply their knowledge, training and skills in new situations and contexts. This will enhance workers' ability to adapt to the rapidly changing manufacturing environment.

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- Textile Mill Products
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- Chemicals Manufacturing, Except Drugs

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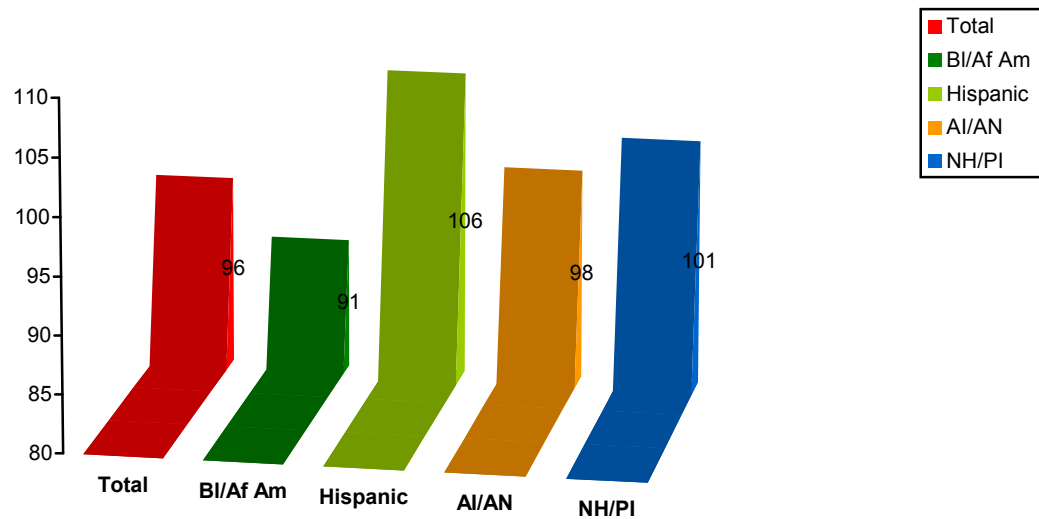


Figure 4.3.1. Male-Female Ratio by Race and Ethnicity for the United States 2000

BI/Af Am = African American

AI/AN = American Indian/Alaskan Native

NH/PI = Native Hawaiian and other Pacific Islander

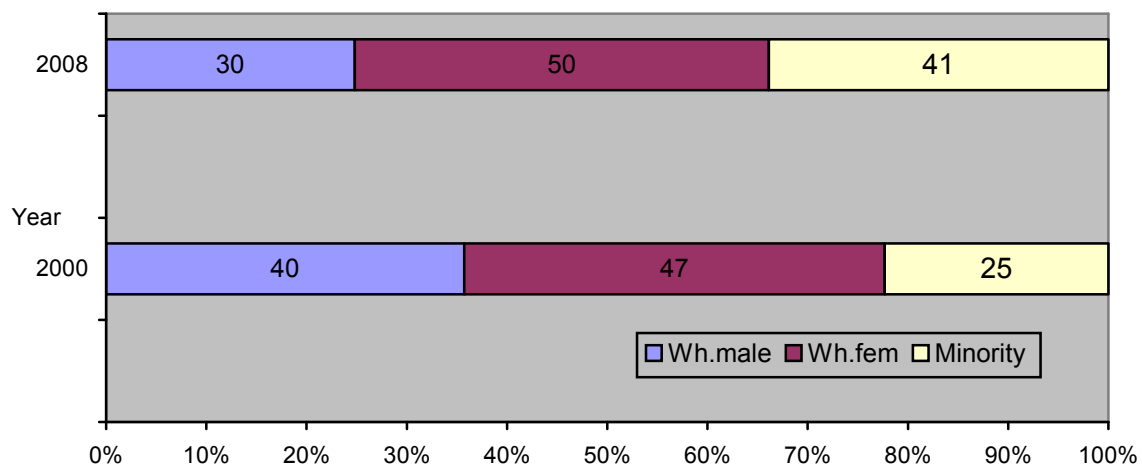


Figure 4.3.1a. Demographic changes in U.S. workforce: 2000 and 2008.

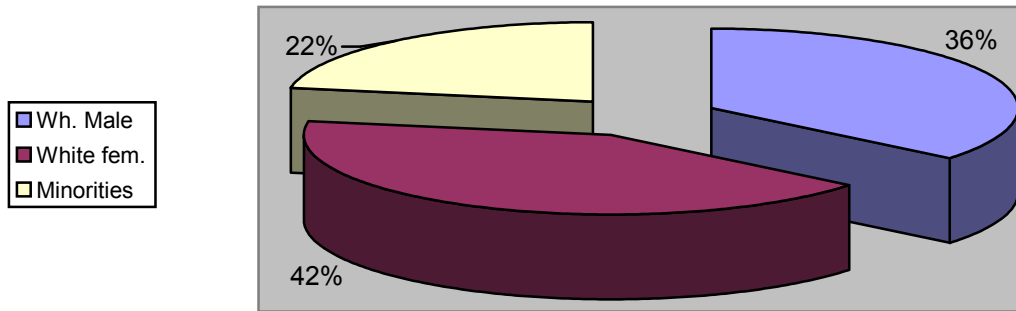


Figure 4.3.2a. Demographic composition of U.S. labor force 2000.

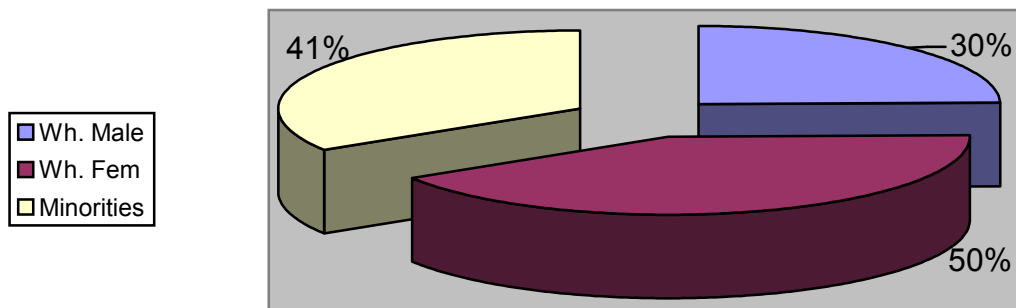


Figure 4.3.2b. Demographic composition of U.S. labor force 2008 (projected).

4.4

Discussion of Panel Presentations. Organizing Manufacturing to Compete at Global Scales

Danyluk. Professor White, the gatekeeper in security is the government so far. Are there any discussions about companies providing the data to get beyond this gatekeeper?

White. The best practices for ports are akin to QS 9000, or based on initiative of the participants. Cooperation with the private sector is also an important practice.

Tannenbaum. Professor White, do our competitor countries have the same kind of security issues that we do?

White. Yes, they have inherited our problems. For instance, Siemens and Bosch are affected by the same regulations at the U.S. ports. However, the primary problems are at the megaports. U.S. companies are trying to do all inspections in Singapore – the practice is called “pushing back the borders.” Such practice has value from a security point of view, but it is not helpful from the productivity point of view. It might take so long to inspect the container that one may miss the boat, and the next boat may be sailing only 3 days later, or even 8 days later for a small port such as Savannah.

Danyluk. Mr. Estes, what percentage of pulp and paper production uses recycled materials and processes?

Estes. The percentage is quite significant. There are three main areas of pulp and paper production process where recycling is used. They are water reuse, recovery of auxiliary chemicals, and post consumer products such as paper.

Mistree. Professor Leggon, what should be an appropriate engineering curriculum?

Leggon. There are some discussions and disagreements as to what should be included in an engineering curriculum. Some bemoan that computer-aided design prevented engineers from getting a broader sense of changes in the general environment. Others maintain that innovation is great, but our engineers should have well-rounded skills. For instance, they should have excellent literary and art education, not just be technically skilled. Should engineers specialize at the undergraduate level or should they wait until they get into a graduate school? Should they be able to apply skills across fields? It is important not to think in disciplinary boxes.

White. What aspect of U.S. engineering education makes our engineering student competitive vs. bright engineering student coming out of IIT in India or China with a much lower pay rate?

Leggon. Ability and readiness to apply their skills. This in turn is taught by professors. When engineering faculty go on sabbatical, they are able to come back to the classroom and give students the skills they need.

Shapira. There is also difference in the quality of educational output. For instance, Malaysia has a good university system. Yet there still difference comes in the qualities of their student output – and these are mainly on the side of “soft skills,” for example in terms of engineering entrepreneurship, team work skills, or approach to innovation and risk. We have to think of ways to maintain and strengthen such skills in U.S engineering education.

5

Concluding Comments

5.1

Reflections on the History of the Future of Manufacturing Technology

Robert McMath¹

History does not repeat itself, but sometimes it rhymes or echoes. The second industrial revolution of 1880-1930 gave rise to GA Tech and the drive to develop manufacturing capacity. We are now entering a new industrial revolution. In this workshop, three themes of this new revolution emerged, in each of which you may hear an echo and a rhyme of the history of our earlier industrial revolution. The three themes are: mass customization and/or flexible production, nano technology, and self assembly.

The first thing we think of when we discuss conventional manufacturing is mass production. The fact of the matter is that much of the even previous manufacturing was in the form of flexible production. Take for example the numerous communities of best practices, and communities of discoveries. Many of them were based, in like industries, within the same sites. Custom manufacturing is not new and it is not driven out by mass production.

The second theme we discussed was nanotechnology (and I am finally coming to understand some of this). Rina noted that something big is about to happen, something that will turn things on a dime the way that the silicon chip did. Yet it is not yet clear in which ways this will happen, when and how. The second industrial revolution grew out of the efforts that harnessed our competitive advantage. These were explicit efforts. Technologies do not fall from the sky; they come into organizations with leaders that are capable to put forth various and complex ideas to practical uses. Perhaps here we should think again about what types of leaders are capable to realize the promise of the next industrial revolution. Would it be a new kind of engineer? Would it be still an engineer, but also a generalist and a collaborate leader? Should we concentrate on both high-powered math skills as well as creativity (engineering creativity) and ability to lead, ability to translate the nascent ideas into working technologies?

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The third theme is on self-assembly, or genetic assembly. This a marvelous theme to contemplate in some ways. Think of the body politic during the second industrial revolution. In many ways the revolution was about jobs, as the threat of loss of jobs politicized plants. Remember when Andrew Carnegie stood up in front of his workers and said: “Mr. Carnegie takes no man’s job.” Today when we are discussing the future forms of manufacturing such as self-assembly, the first group of people who will be affected by it are the workers. Hence we are talking about a different type of workforce. We are talking about R&D jobs forming the biggest part of the market—R&D becoming the biggest employing sector, or the most labor-intensive sector. The assumption we are making is that excess workforce will be absorbed as it happened in the late 1880’s when Chicago absorbed the influx of settlers from the partially depopulated Midwest. Will our cities be able to do that again? Will there be some kind of public policy to assist both people and governments?

I am not sanguine that we will be able to help people to get back on their feet. Our government may not have the political will. Yet we need to address the issues of labor force and employability. For instance, work in R&D will require a Ph.D. degree. What should we do with those who do not have such degrees? We need to think of these issues now.

5.2

Discussion

Danyluk. Bob made me think of the issue of losing jobs vs. getting rid of jobs. Unfortunately, one of the functions of engineering is getting rid of jobs. We are producing machines that reduce human participation. This is a paradox, and somehow our society has to solve it.

Mcmath. You create the problem and society has to solve it.

Danyluk. Does anyone in the room remember women telephone operators? It is almost unimaginable how many women operators we would need today with all the telephone numbers we have.

Mcmath. The 1960s and 1970s experienced an expanding economy. Timing, in this regard, is everything—within an expanding economy, it is possible to absorb folks. I take your point, the job of engineers is to create greater efficiency. We can overstate that. The real history of mechanization of cotton farming took millions of people off the land. However, there are different types of efficiencies – some would have greater efficiencies plus higher level of employment than other kinds of efficiencies.

White. Sometimes the labor is redirected in a good way and sometimes it is not. Sometimes we lose jobs and sometimes people can find themselves in higher paying jobs. But often it is not easy. There are winners and losers.

Mcmath. That is right, and losers are still here. They will create their own solution.

Danyluk. That is the reeducation.

Ellington. This is where history can help us out. In the 1950s, 1960s, and 1970s our environment was closed. The environment is now exponential – the losers do not have any place to go because the winners are losing jobs to the losers. We are in unprecedented times. We do not have models to predict this. We do not know how fast things are going to move. In the Department of Commerce we do not have data sources that move fast enough to do us any good. The Census of Manufacturers is released only once every 5 years.

Mcmath. Take the example of classic migration of low skills low wage jobs. We are in the unprecedented times—we witness the globalization of knowledge. Shutting off national borders is an anachronism. As we continue, we know that there is a slight decline of the number of applications to GA Tech and other similar schools. What are young people saying? Are these engineering jobs going somewhere else? What does this say for us? The old pattern of low wage low skill already happened to engineering professions.

Meindl. There are 4 key things that have to be done to maintain us competitive: First, have to have the best education system in the world – from K through 12 grades. When our students are compared with other countries, we don't want to be Number 15, we want to be Number 2. The quality should extend into graduate programs – when an engineer comes out with an MS or Ph.D., they should be better qualified than those coming out of the IIT.

Second, we have to be Number 1 in support of R&D. Our research support especially from the government is going down. We have to reverse that. We need more government and corporate money. We need various fiscal policies that encourage investment.

Third, we also need the world's best knowledge infrastructure akin to the interstate highway system constructed in the 1950s. We need a wideband network that brings fiber to home and a two-way video communication. Fourth, we need government regulations and initiatives that do not harm our competitiveness. For instance, we can not treat stock options as expenses.

I would like to add another point: The Semiconductor Industry Association maintains that R&D is intimately coupled to state of the art manufacturing. The Intel policy is to copy exactly. Take a R&D fabrication line. Intel copies every feature of that line into the production line; ramp up is a matter of a few months. And every generation has to ramp up faster because of the need to recover billions dollars worth of investments

White. Let us look at infrastructure. China invests a much greater percentage of GDP into infrastructure than we do. Additionally, their students are much better than ours. It is hard to imagine being number one in all the areas you mention. The implication is that there will be a wage adjustment in the middle class. Economists are now talking about the bottom 95%.

Meindl. Then, our bottom 95% has to be better educated than their bottom 90%.

Shapira. Let me play back the themes that we identified as potential trends of the future of manufacturing. First, the shift from mass production to mass customization. Second, the shift from interaction between manufacturers to the integration of manufacturing – using such technologies as distributed manufacturing. Third, the importance of developing communities of practice and supportive infrastructures to promote and diffuse innovation. And, finally, the rise of nanoscale manufacturing. Perhaps there is an analogy here. The smaller the scale at which manufacturing occurs, the larger is the area which interconnects us; and it is these interconnections that will become the critical issues. Perhaps, future jobs and professions will be based on and in these interconnections. For instance, the majority of “manufacturing” jobs will be not in manufacturing as we know it today, that is on the shop floor, but in related services or R&D, etc.

There are other overarching themes that are also important. How can we deal with a shift of control from centralized to more distributive modes of manufacturing? Also, what about the theme of sustainability and environmental lifecycles in manufacturing, which we have not touched in great detail today? The workshop themes we did discuss revolved mainly around the issues of transforming jobs to wealth and vice versa. Concerns were raised over demographic and human resources, restructuring of education, and the reconceptualization of management. Finally, an issue of globalizing security was raised as something new about the world environment and how we relate to it and how it affects manufacturing and design.

5.3

Closing Remarks

Ned Ellington¹

Washington D.C. in general, and specifically the Department of Commerce (DOC) needs to find out more information about what is going on in manufacturing. We also need to get involved with the public discussion. These workshops feed us with the big picture of where manufacturing is going. Last year the DOC was pulled together by the manufacturing initiative, in which the DOC produced a strategy on manufacturing. It was a good first step. The intention is to reverse the cycle of 30 months of job loss in

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manufacturing. The department will hire a manufacturing czar, who will be an assistant secretary and at the White House level. This person will come from the private sector.

The manufacturing initiative will be under the umbrella of the International Trade Agency (ITA), which is the largest group in the DOC. There were hopes that manufacturing could be placed in the technology administration. This reflects the current view of many policy-makers in Washington on manufacturing as a process consisting of several value streams. The streams that they are focused on are sales and services. We need to make them understand that manufacturing is also about design and technologies.

The fact that we do not collect data, which would enable appropriate policy analysis, does not help.

Many members of the Congress raise voices about the manufacturing crisis from the perspective of losing jobs, revenues, and trade deficit jumping through the roof.

Our message is that we need both leadership and a hands-off policy. Your message that we have lost the track of R&D is received loud and clear. The issue of education is problematic and looms large in Washington. It seems that policy-makers are a little hesitant as to how deal with the issue, and the general tendency is the belief that we have to tackle the issue in big buckets. It is interesting that we can custom-design a car, but we can not figure out how to structure the education process. Yet, it is clear that our technological advancements are contingent on education.

With the Presidential elections this year we hope that manufacturing issues will have a strong voice in Washington; hopefully we will maintain the momentum.