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

by

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\textbf{Keywords}: Technology forecasts, Manufacturing modernization, Manufacturing History

November 2006

\textbf{Acknowledgement}. The research presented in this paper was funded by the Manufacturing Futures Group of the Manufacturing Extension Partnership (MEP), National Institute of Standards and Technology (NIST), U.S. Department of Commerce.
Abstract

This paper reviews past manufacturing technology forecasts over the last five decades relative to the realization of these predictions. 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.
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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 computer use (in the 1950s through the 1970s) and later Internet technologies were far outstripped by rapid rates of email, Web, and network adoption in the 1990s and 2000s, 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 with a discussion of selected technology forecasts and predictions in reports published in successive decades from 1950 through to 2000 (See Table 1). In selecting these publications, the aim was to address major research works and policy reports that typified discussions in their time period about concepts such as “future of manufacturing,” “future factory,” “critical technologies,” “next generation manufacturing,” “technology foresight,” and “technology road mapping.” A standard way to identify such documents is to apply these concepts as terms in a search strategy of databases such as Science Citation Index (SCI) or Social Science Citation Index (SSCI). An initial search using these terms together resulted in 1,349 publications, which was too large of a number to review. In addition, no publications from before 1965 were available and few were really present prior to the mid-1980s (see Figure 1). But more importantly, such a search excluded some non-peer review policy reports and “gray literature” that nevertheless had an impact on the debate about future technologies and policy considerations such as the Making Things Better report from the Office of Technology Assessment (OTA). A further search of the National Technical Information System (NTIS), with its emphasis on government-funded scientific and technical reports, also did not include much information about reports prior to the 1980s and was also missing the aforementioned OTA report. The need to access earlier information about future-forward manufacturing technology documents prior to 1980 required trips to the university book holdings and archives. In addition, there was an effort to focus on publications with relatively near term forecasts (10 years or less) that reflect the decade, rather than highly futuristic predictions such as in science fiction. Authors’ knowledge of policy documents and major research and Web searches supplemented formal
searches of research databases. Nevertheless, it is acknowledged that the representativeness of this analysis is limited by the selection of the forecasts profiled here.

2 Five Decades of Manufacturing Technology Predictions

The next sections review historical predictions about the future of manufacturing technological innovations. This literature is presented on a decade-by-decade basis.

2.1 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.

*Automation: The Advent of the Automatic Factory* (1952). Conventional views of automation linked it with the automobile industry. John Diebold’s influential work outlined the potential role of automation to the daily operations of a range of manufacturing and other businesses. His work also was important in that it referenced not just the machine but also the processes important to making the machine work. Diebold’s concern about the ability of automation to apply to short production runs set up a tradeoff of scale versus flexibility which characterizes current challenges to customize manufacturing operations.

*Toward the Factory of the Future, 1957.* This American Management Association report emphasized the link between computerization and quality processes in the future. Future plants were foreseen to be empowered with digital computation and linear programming, giving them inventory and statistical quality control capabilities (AMA, 1957,
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). In addition, *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). The report rightly linked automation, processes, and workforce, albeit through a mass production lens.

*Automation in Business and Industry*, 1957. Eugene Grabbe’s work pointed toward future challenges in efforts to further automate production. This book criticized “black-box” approaches to implementing automated control functions. Grabbe had the foresight to project that the costs to design the automatic features, quite high at the time, would pale in comparison to the costs of redesigning the larger surrounding production systems. However, Grabbe had an overoptimistic perspective on the ability of automation to reduce the rate of natural resource consumption, given that the reverse has continues to occur in the developing world.

2.2 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 continuous processes that could be fully controlled (such as rubber, telecommunication, fiber and food products) but less likely in discrete industries (such as furniture production or mining). Buckingham also predicted that automation could actually increase operating expenses, suggesting that he was unable to foresee future productivity gains from computerization. He noted that to
reduce the costs of raw materials, manufacturers of the future would place greater emphasis on the use of manmade resources and less emphasis on natural products, which is arguable in the competitive energy market of the 2000s. He also predicted that automation would lead to further declines for low-wage, lagging regions and job losses among middle managers, again not foreseeing the ability of information and communications technologies (ICT) to spread of manufacturing to low-wage regions and countries.

*The Age of Automation, 1965.* Leon Bagrit (1965) envisioned that automation would result in consolidation of establishments into large corporations and the disappearance of small manufacturing, something that still has not occurred in the 2000s. He also raised concerns about job losses, particularly at the lower skilled ranges of the workforce and among minority groups, which could arise from automation. (p. 104) His projections further emphasize the link between workforce and technology, although he underestimated the importance of dynamism in the economy and the role of the smaller niche manufacturer.

*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. He argued that most U.S. companies initially produced new products in America to keep production facilities close to the early 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 would become more standardized and cheaper. 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. Vernon’s work has since been re-evaluated in light of current decentralized competency perspectives based on the observation that firms in the 1990s and 2000s began to outsource R&D to highly capable low cost regions in Eastern Europe and Asia.

2.3 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 less developed countries to take advantage of lower labor costs. He predicted that such activities would be considerably expanded in the future, with technological progress in the advanced countries leading to substitution and economies in the use of raw materials. The terms of trade would be turned against less developed countries dependent on the export of raw materials. This forecast about less developed countries being disadvantaged has proved to have limits in light of trends toward freer trade and technology transfer.

*The Third Industrial Age: Strategy for Business Survival, 1975.* In contrast to Pavitt’s view of the impact of technology on lesser developed countries, Charles Tavel (1975) believed that developments in transportation, computers and communications would actually enhance the bargaining power of these countries with multinationals. Tavel predicted that the
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). This viewpoint resonates in contemporary discussions about the need for innovation in manufacturing.

*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 foresaw a post-industrial society in which manufacturing would grow at much slower rates in the future, with fewer jobs manufacturing things and more emphasis on the pursuit of creative mental work tasks under less hierarchical more egalitarian participatory management structures.

*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, leading them to use systems 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 would be subject to these trends. The beginning of leading edge use of computer control systems underlies the Bell-Braverman perspective on the impact of these and other technologies on workforce issues, and whether such technologies enhance or deskill human capital. This debate remains relevant today.
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.” Davis anticipated that the computerization of control process would result both in substitution of computer control for traditional control systems and in the invention of entirely new processes not previously possible without computer control. But he was troubled that the pace of advance in computing would be agonizingly slow. As with many predictions about the growth of computing, Davis’s estimate fails to account for changes in the computing industry such as the growth and pervasiveness of ICT in the 1990s and 2000s; for example International Telecommunications Union (2006) reports there were 775 million personal computers in 2004 (and even more devices that act as computers).

2.4 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. 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).

*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). These included new materials (e.g., polymers and ceramics); the concept of a fully automated factory revived through computer integrated manufacturing (CIM); quality-based practices such as employ empowerment, coordination of design, cross-training, and use of information to track performance. This report reflects the overemphasis of the 1980s on fully automated integration as opposed to the extended supply chains of the 1990s and 2000s.

*Getting Control of Just-in-Time, 1989.* Karmarkar’s article emphasized the importance of integrating manufacturing resources planning (MRPII) with Just-in-Time (JIT) (Karmarkar, 1989). MRPII was regarded as an extension of materials requirement planning (MRP), in that both addresses the need to divide the manufacturing process into segments and integrate information about these segments into a central database, although MRPII was believed to have superior production initiation, order releasing, and inventory reduction offsetting capabilities. Karmarkar projected that the major barriers to adoption of MRP and MRPII were (1) the initial cost of installing and maintaining the system, including both hardware and software investment and workforce training expenditure, and (2) fixed lead times and lack of responsiveness. He suggested the integration of MRPII and JIT would take advantage of both systems and work flexibly in different environments. These technologies foreshadowed lean production systems, but they were limited in their ability to take into account the needs of other enterprise functions and supply chains.
*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.” Seeking to explore the future of integrated manufacturing technologies and techniques, this book predicted that flexible production equipment with analytic and predictive capabilities would be more widely adopted in the future given the increased pace of international competition and the shortening of product life cycles. Emphasis was placed on the electronics industry’s short average product life cycle of 18 months, which has since been reported at six months in the 2000s. (IBM, 2006) Another forecast was that cost reduction measures inherent in inventory management and synchronization of supply and demand would be critical for future competitiveness, which continues to be evidenced in the lean manufacturing movement into the 2000s even as contemporary thought emphasizes innovation in addition to cost reduction for competitiveness.

*Made in America: Regaining the Productive Edge, 1989.* This book was the result of the MIT “Commission on Industrial Productivity,” which focused on eight industries: automobiles, chemicals, commercial aircraft, consumer electronics, machine tools, semiconductors, computers and copiers, steel, and textiles. Six problems which deteriorated productivity performance were identified: (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. The report provided recommendations to improve manufacturing, workforce training and job security, promote employee empowerment, penetrate more international markets, and gear
macroeconomic policies to encourage long-term investments. The report’s gloomy outlook for the U.S. manufacturing productivity in the 1990’s was somewhat at odds with the recovery of manufacturing and productivity gains in that decade.

2.5 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. The report offered several policy recommendations 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 report also demonstrated how the spillover effects of technology transfer may foster a broad range of manufactured products, such as in the case of high definition television and other advanced television technologies (ATV) on computer, telecommunication, and other electronics industries. This report was seen as one of the origins of several significant federal initiatives including the Manufacturing Extension Partnership program and the Advanced Technology Program.

*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 of the National Academies developed a series of publications about advanced manufacturing technology. The report predicted 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 control and integration themes of the 1980s are evidenced in these predictions. In addition, The Competitive Edge projected that the manufacturing workforce would decline in the 1990s such that it would be 20 percent lower in 2000 than in 1950. Despite the economic downturn at the turn of the century, this was not the case. Even though the modern peak of manufacturing employment in the US was 19.4 million jobs achieved in 1979, the manufacturing workforce in 2000 was actually more than 20 percent bigger than in 1950.

*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
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 limited view that major breakthroughs in usage of composites had already happened, reflecting a lack of molecular perspective on materials advances.

*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. Marshaling Technology expressed expectations for electronics growth associated with developments in silicon, protonics, fast software development, and integrated circuit technologies. The report expected electronics firms to adopt computer aided design (CAD), integration of design/ manufacturing/marketing, and CIM as a means of producing life cycles, and that this adoption of CAD and CIM would eventually spill over into other industries; this proved more to be the case for CAD than for CIM in the 2000s. Although biotechnology was also believed to be a cutting edge research area for manufacturing, it was perceived as too futuristic for commercial exploitation; even a decade later biotechnology is viewed as taking a length of time to begin to show significant commercial promise.

*National Critical Technologies, 1991, 1993, 1995, 1998.* The 1990 Defense Appropriations Act established a requirement for creating and maintaining a National Critical Technologies (NCT) report. Critical technologies were defined as advanced, essential for national security, useful for important products and applications, and likely to impact many product applications. The lists were developed through consensus-based approaches involving panels of experts. The 1995 NCT list included 48 specific technologies
divided into discrete product manufacturing, continuous materials processing, and micro/nano fabrication and machining. Popper et al (1998) provided an enhanced operationalization of critical technologies based on cross-sectoral ubiquity of ICT and sensor technologies; technologies at the interstices such as separation, overhaul-and-repair, and complex-product system-coordination technology; and technologies for society (Popper et al, 1998). Subsequent years have shown that the act of creating lists of militarily important technologies does not necessarily ensure follow through to the ongoing development of these technologies or other aspects of the policy process. (See for example, Calvaresi-Barr, 2006.)

*Unit Manufacturing Processes, 1995.* This report (UMPRC, 1995) highlighted 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, material behavior opportunities included 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. Although this report did draw attention to the importance of enabling technologies, it did not devote enough attention to the ICT revolution.

*Next Generation Manufacturing, NSF 1995.* NSF was the lead sponsor of the Next Generation Manufacturing (NGM) project, which used more than 5000 experts to put forth a vision of the future of manufacturing (NSF, 1995). Next generation manufacturing was defined as an enterprise that extended from “the supplier’s supplier to the customer’s customer.” The report predicted a future shift in business practices from lean manufacturing to agile manufacturing, replacement of narrow computer-controlled machine tools with rapid prototyping and free form fabrication, and a blurring of the line separating manufacturing and
service industries would become increasingly blurred and new definitions of industrial 
activities would emerge. These broad trends were evidenced in subsequent years, particularly 
the role of supply chains, although lean manufacturing and existing definitions of industrial 
activities continued to prevail in many 2000-era manufacturing operations.

*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 for 2020 to develop revolutionary thinking about 
manufacturing based on a workshop of academic researchers in manufacturing-related 
disciplines and a survey of industry experts (CVMC, 1998). The report identified six critical 
directions (i.e., grand challenges) in manufacturing: (1) concurrent manufacturing, (2) 
integration of human and technical resources, (3) knowledge management, (4) environmental 
compatibility, (5) reconfigurable enterprises within and between organizations, and (6) 
innovative processes for customization, miniaturization, and new material fabrication. The 
promise of biotechnology received particular emphasis. This report continues to influence 
research and practice in the 2000s, particularly efforts to develop freeform on-demand 
manufacturing platforms.

2.6 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), sponsored by five major US departments and corporate members, developed five roadmaps for: (1) information systems, (2) modeling and simulation, (3) manufacturing process and equipment, (4) technologies for enterprise integration, and (5) intelligent controls. Forecasts in this report included the move from lean manufacturing principles to technological opportunities in areas such as freeform fabrication, newly engineered materials, and micro and nanotechnologies; the move beyond enterprise tools such as enterprise resource planning (ERP) and product data management (PDM) to systems linking internal functions and external partners; the move beyond process technology to zero net lifecycle approaches; and the move beyond analysis of basic data to best practice based on knowledge management techniques.

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 rely on just-in-time low inventory systems, suggesting that the rate of implementation of techniques such as six sigma, ISO certification, and statistical process control therefore is expected to increase. Manufacturing enterprises were also expected to invest more in supply chain communication systems, flexible manufacturing techniques, and sophisticated logistics systems. It was recommended that SMEs make effective use of Internet and Web technologies and 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. Richards et al (2001)
project that information technology could be a potential substitute for physical products, depending on continued reductions in the cost of information processing and other factors. It was recommended that sustainability be incorporated into product development stage gate processes and that recyclability be integrated into modular design through methods such as quality function deployment and design for assembly tools. The report forecasts that energy is likely to be more expensive and to shift from primary fuels to electricity, requiring new energy infrastructure to accommodate these trends. The energy challenges faced in the mid-2000s and the substitution of on-line music for CDs could be argued to be foreshadowed in this report.

*Modeling and Simulation in Manufacturing and Defense Acquisition, 2002.* The National Research Council (NRC) formed a Committee on Modeling and Simulation Enhancements for 21st Century Manufacturing and Acquisition to support the U.S. Department of Defense (DOD) in efforts to make better decisions in combat situations and speed up commercial manufacturers’ ability to “quickly innovate, design, and produce the ‘right product right’ the first time” (BMED, 2002). The report anticipates that basic research will be conducted in areas such as scalability and object oriented technology, multiresolution modeling, 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 situations. The enhanced use of modeling evident in 2000s-era R&D activities is viewed as being dependent on shared process, database, standards, and architecture infrastructures.

3 Discussion
A discussion of these outlooks on manufacturing technology suggests that some provide an early foreshadowing of later developments whereas others are at odds with future events. These works from the 1950s do provide an early forecast of the role of automation and computing in manufacturing, as well as the importance of the processes underlying this automation, and its impact on workers. However, their predictions about automation, digital computing, and advances in inventory control were influenced by the rise of mass market expansion, mass production assembly lines, and high cost of computing. Hence they were unable to account for advances in computing capability and power that took place in future decades that enabled the handling of shorter production runs, even though the scale versus flexibility debate still remains at issue in the 2000s. These early works also presaged ongoing fears about automation, workerless factories, and the issue of a shortage of engineers, which also continues to be current.

Manufacturing forecasts of the 1960s kept automation at the center of leading edge technologies. Scale versus flexibility considerations are evidenced in sixties-era predictions about automation being limited to large continuous process industries, rather than the customization and niche product support systems that drive current leading edge technologies and techniques. As well, computing was associated with higher costs; Moore’s Law improvements and lower long-term cost reductions were not foreseen. In addition, Vernon’s vision identified the ability to divide lower value routine manufacturing and higher value R&D functions and locate them in different regions. However, more than 40 years later we are seeing a recoupling of these activities as R&D is increasingly outsourced to lower cost, highly competent Asian enterprises.

Predictions of the number of computers in the 1970s likely seemed high at the time but have since proved to be more than an order of magnitude off 30 years later. However, management predictions were closer to current practice. Pavitt and Tavel foreshadowed
multinational business strategies that move beyond the bounds of vertical integration, conventional batch manufacturing, and excess inventories. Worries about the impact of manufacturing process technologies on job quality and whether it enhances (as Bell suggested) or deskills (as Braverman suggested) very much colors present management and policy concerns.

Technological predictions in the 1980s reflect an era of enhanced adoption of computerization in manufacturing through technologies such as MRP II and CAD as well as the take up of quality and Toyota production methods to enhance competitiveness relative to high wage manufacturers in Japan and Germany. However, hindsight suggests that forecasts from this period over-exaggerated the adoption of fully integrated manufacturing facilities, and failed to account for the importance of supply chains in production and other practices required by ever shorter product life cycles. In addition, outlooks proposing limited prospects in polymer and ceramic chemistry for materials advancement have been supplanted by molecular-based materials discoveries in the 1990s and 2000s.

The 1990s opens with an economic downturn and preeminence of competition from Japan and Germany that influenced early decade forecasts about the viability of manufacturing in the United States. These projections underestimated the growth of ICT and the Internet boom, and the eventual impact of these technologies on manufacturing productivity and the recovery of the sector. The nineties also saw a rise of more formalized technology foresight activities through the development of critical technologies lists and roadmaps. The extent of influence of these activities on public or commercial activities is debatable, however, with the exception of planning within certain industries (such as the semiconductor industry) or federal agencies. End of the decade predictions were shown to place emphasis on biotechnology and genetic engineering, global production networks, and lean manufacturing.
Concerns about manufacturing’s vitality in a declining economy with more intense low-cost competition in mature e-commerce experience re-emerged in the 2000s. Leading edge information technologies for modeling and simulation, knowledge manager, and supply chain system management were advanced and predictions about the ability of information technology to substitute for physical goods and the role of nanotechnologies proposed. The promise of nanotechnology was accentuated. The importance of innovation and creativity are suggested in growing references to product-based technologies as opposed to lean manufacturing processes. It remains to be seen whether these directions will be upheld or whether they are simply a reflection of the domestic and global economic climate.

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, management, and workforce trends. (See Table 2.) 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, which require flatter organizational hierarchies bestowing responsibility on empowered employees. 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 characterized by joint ventures, inter-organizational partnerships, and customer-centric exchanges.

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 also increasingly upgrading its technological capabilities.

[INSERT TABLE 2 ABOUT HERE]

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. The need for US workers to be better and more flexibly trained in multidisciplinary and technical skill areas is emphasized in the 1990s and 2000s if manufacturers are to compete based on innovation with low wage but highly proficient global counterparts.

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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<th>Author</th>
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<td>Leading-Edge of Current Technologies</td>
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<tr>
<td>1950’s</td>
<td>Rise of post-industrial society; Mass market expansion and stable economic growth in manufacturing</td>
<td>Mass-production; assembly line; dedicated tools Emergence of real-time processing – but with high cost</td>
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<td>1960’s</td>
<td>MNC’s shifting to low-wage companies; Growing economy; The increase of the geographical mobility of industry; Expansion and diversification of enterprises</td>
<td>Greater emphasis on the use of gasses, liquids, electric power, and pure compounds and lesser emphasis on natural products, crude mixtures, and solids</td>
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<td>1970’s</td>
<td>Continued globalization; Declining economy; Slower rate of growth for manufacturing; The creation of new science-based industries; Geographical expansion; Environmental regulations effecting traditional industries</td>
<td>NC Tools; Microprocessor; Microelectronics; Multiple processor on chip; Computer control ‘boom’</td>
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<td>1980’s</td>
<td>Intense globalization; Growing economy; Increasing speed of changes in the overall economic environment</td>
<td>CIM; MRPII; CNC, EDM; CAD; Robotics; Control systems (Computer control, robotics); AGV; Automatic recognition systems; MAP; New materials: polymer, ceramics; FMS</td>
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<td>1990’s</td>
<td>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 U.S.; Recovery of manufacturing; Industrial concentration/selected industries; Industrial ecology; Fast advances in Information Technology; Intersectoral flow of technologies</td>
<td>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; Nanotechnology, new materials (manipulate molecules); Life sciences</td>
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<td>2000’s</td>
<td>Declining economy; Mature E-commerce</td>
<td>Rapid prototyping; Freeform manufacturing; Net-shape and fixtureless processes; Ultra high-speed machining; Intelligent assembly; Flexible material handling; Remanufacturing technologies; Modeling and simulation; InfoSleuth™</td>
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Figure 1. Publications combining topical focus on future manufacturing technologies.

Source: Search of ISI Web of Science, Science Citation Index and Social Science Citation Index, October 2006. All publications topic search term = (future NEAR manufacturing) OR (future NEAR factory) OR (critical NEAR technolog* NEAR manufacturing) OR (next NEAR generation NEAR manufacturing) OR (technology NEAR foresight AND manufacturing) OR (technology NEAR road$map* AND manufacturing). N=1349.