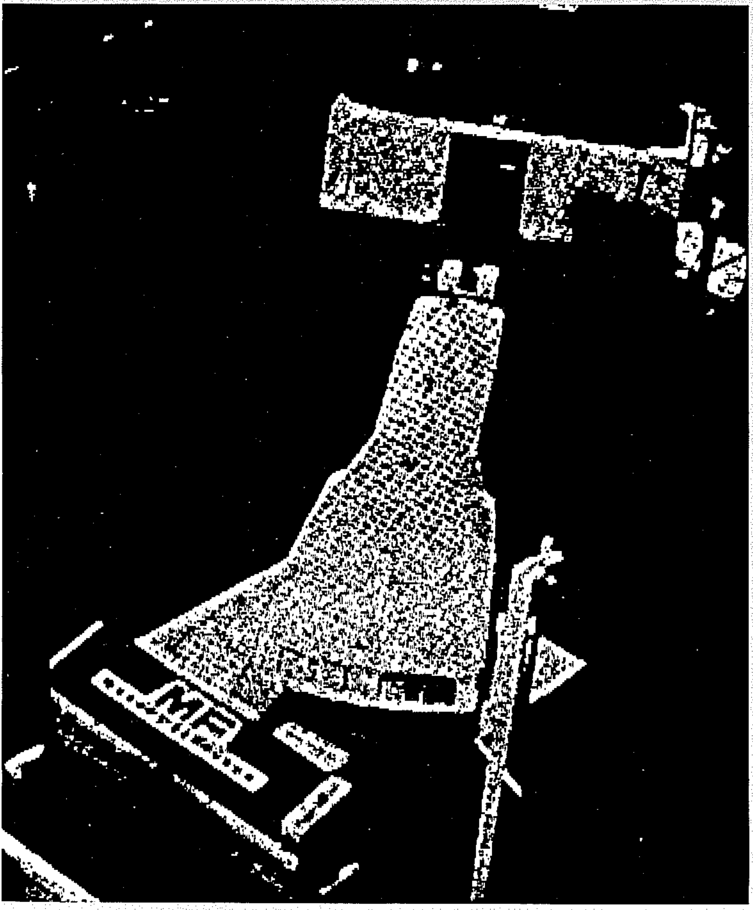
THE MATHEMATICAL AND COMPUTATIONAL SCIENCES IN EMERGING MANUFACTURING TECHNOLOGIES AND MANAGEMENT PRACTICES

Avner Friedman James Glimm John Lavery



SIAM Reports on Issues in the Mathematical Sciences

Science and Industry Advance with Mathematics

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Published by the
Society for Industrial and Applied Mathematics
Philadelphia
1992

Cover: Robot carrying out parts transfer operation. Photo courtesy of General Motors Corporation.

For additional copies write:
Society for Industrial and Applied Mathematics
3600 University City Science Center
Philadelphia, PA 19104-2688
USA

Printed in the United States of America

Preface

A global manufacturing economy with its increasing demands for advanced technologies and improved organization is upon us. To remain competitive, the United States must meet these demands. The traditional build-test-fix and build-sell-repair cycles have become too expensive. They are being displaced by more systematic approaches, ones based on quantitative methods, that is, on the methods of the mathematical and computational sciences. Increasingly, the mathematical and computational sciences are being requested to accelerate technology transfer and to become more deeply involved in developing tools for management decision making in manufacturing.

Macroeconomics, regulatory policy, tax policies, interest rates, management practices, labor-management relations, advanced technology, and education all have a bearing on competitiveness in manufacturing. The development of strategies that enhance manufacturing capabilities requires cooperative efforts from many groups in our society. The focus of this report is on the contributions that the mathematical and computational sciences community make to technology, management, and education for manufacturing and on the opportunities for mathematical/computational research that manufacturing creates. Often these contributions are made through cross-disciplinary efforts and involve collaborations with applied scientists, engineers, management specialists, social scientists, and economists.

Mathematical and computational scientists are presently participating in creating the new technologies and management principles needed for manufacturing success in a global economy. Although the mathematics and computing communities are paying increasing attention to manufacturing problems, the pace of this work is not sufficient. One of the goals of this report is to encourage more rapid progress by identifying those areas of the mathematical and computational sciences that are needed in cutting-edge manufacturing. A second, equally important goal, is to provide information to the manufacturing management community on the role of quantitative methodologies in solving the problems they encounter.

Thus, we address the mathematical and computational sciences community and the communities of applied scientists, engineers, social scientists, and economists in industry and academia with which it interacts. We address also the managers and decision makers in the manufacturing community, especially those responsible for the integration of new technology and management principles into the manufacturing enterprise. We point to the large number of ways in which the mathematical and computational sciences are already contributing to manufacturing. We also indicate areas in which further mathematical/computational research is required to satisfy the future requirements of manufacturing.

This report is one step in defining the interaction and collaboration of the manufacturing community and the mathematical/computational sciences community. An in-depth examination of these issues, including perspectives from specific industries, is called for. Topics that could not be included in the present report—tolerancing, testing procedures, integration and "understanding" of sensor data from diverse types of sensors, models of manufacturing processes that can be incorporated into larger models of manufacturing units, and service functions such as marketing and delivery—could be treated in an in-depth report. Such a study should include an assessment of the interaction in Europe and of that in the Pacific Rim as bases for comparison. A matrix cross-indexing manufacturing and management technologies with distinct mathematical and computational technologies would be helpful. Also called for is a separate study on the interaction of the mathematical and computational sciences with the service sector—communications, transportation, shipping and delivery, health care, marketing, the securities industry, and financial services—which in dollar volume is some three times as large as the manufacturing sector.

A report on the intersection of the mathematical and computational sciences with areas as broad as manufacturing technologies and management practices is of necessity limited in detail and limited to a relatively small number of focal points. Within these limitations, however, the authors believe that they have a strong message to deliver in favor of increasing the common interests and activities of the manufacturing community and the mathematical and computational sciences community. The well-being of both communities and of the nation depend in part on this happening.

This report could not have been written without the assistance of many colleagues and friends. The authors express their gratitude to F. Chung, G. Coffman, P. Dautidis, E. Drexler, G. Hahn, D. Hawkins, C. Hoffmann, R. Kaplan, R. Merkle, S. Meerkov, K. Miller, J. Mitchell, V. Nair, D. Robinson, M. Shuler, J. Solberg, A. Tucker, D. Ullman, S. Vardeman, J. Walsh, P. Will, and C. A. Yano, who so generously shared their insight into the contributions of the mathematical and computational sciences to manufacturing technologies and management practices. I.E. Block, J. Chandra, G. McDonald, V. Srinivasan, and J. Wu reviewed the report and made useful suggestions. The report was edited by A. Glimm. The authors' research was supported by the National Science Foundation, Air Force Office of Scientific Research, Army Research Office, Department of Energy, IBM, National Security Agency, and Office of Naval Research.

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September 1992

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Executive Summary

A revolution, one led by the rapid increase of computational capabilities and an increasingly quantitative approach to problem solving, is transforming the manufacturing world. The expensive and time-consuming build-test-fix and build-sell-repair cycles are being displaced by quantitative methods, which increase the chances that the product will be built right the first time it is built.

In the three decades immediately following World War II, a rapidly expanding economy encouraged belief in a system that was already at that time being questioned by some. In that system, the scientists made basic discoveries, the engineers and designers designed, and the manufacturers produced. Optimization of the system was achieved by optimization of individual processes and components. Quality was measured by the absence of defects. With growing global competition, however, a new kind of thinking in manufacturing is emerging, one that engages the totality of the manufacturing system instead of dealing separately with its individual parts. Manufacturing is no longer a collection of separate, highly specialized functional units, or silos, linked in a hierarchical structure by corporate management. Today, a successful manufacturing enterprise is a complex system of interdependent processes linked laterally.

The broad field of manufacturing ranges from the very concrete (materials that go into products) to the very abstract (information management and organizational structure). There is insufficient awareness of the ways in which the mathematical sciences have assisted industry in attaining its current level of achievement in all of these areas. Statistical analysis reduces data from manufacturing processes and systems to meaningful forms. Modeling reduces manufacturing problems to quantitative relations and equations suitable for attack by algorithmic methods. Mathematical algorithms written in computer code, that is, software, express the quantitative relations and equations in a format suitable for computational solution. Hardware produces the raw computing power. The revolution that is transforming manufacturing involves notable progress in modeling, impressive improvements in software, and dramatic advances in hardware.

The report highlights contributions of the mathematical and computational sciences to various contemporary and emerging areas of manufacturing. The enabling role of the mathematical sciences in advanced materials, manufacturing processes, process control, statistical quality improvement, cost-based performance measures, and benchmarking is important in contemporary manufacturing.

Six emerging manufacturing technologies, in which the developments resemble revolution rather than evolution, are highlighted. The first two of these technologies, intelligent machines and solid modeling, are basic technologies that underlie other emerging manufacturing technologies. Rapid prototyping, molecular manufacturing, and biomanufacturing are technologies that did not exist ten years ago but that are expected to be major factors in the manufacturing world ten years from now. Environmentally benign manufacturing is an emerging technological area that is becoming a way of life and will have profound influence in all areas of manufacturing.

Five emerging management practices are examined: operations-based performance measures, computer-based information management, flexible manufacturing systems, capital budgeting for flexibility, and integrated manufacturing. These five areas are all important in the new model for management practice and organization of a manufacturing system. This model is based on decentralization, with increased resources and authority becoming available to employees at the lower levels of the structure. It is based on integration, with distinct functional units communicating transparently and working and planning interdependently. It entails expanded access to information and increased use of quantitative methods, which enable these changes and support decision making by managers. Quantitative methods and tools for management supplement, but do not replace, the traditional humanistic approach to management decisions.

With flatter organizational structures and more inter-unit coordination, employees at all levels of the enterprise require greater technical understanding and communication skills. The emphasis for the workforce in general is on basic quantitative skills that permit the employee to participate in the decision-making process more directly and to make a greater contribution to the enterprise. Technical/scientific personnel need more broadly based experience and communication skills in addition to good technical background. For managers, there is a complementary need for increased technical background in addition to broad experience and communication skills. Continual, life-long learning should be the norm for all production workers, managers, and technical personnel.

The major conclusions of this report are:

- A revolution is transforming the manufacturing process and the organization of industrial enterprises.

- New technologies and management practices enabled by the quantitative, that is, mathematical and computational sciences are among the driving forces of this revolution.

- In their generic and precompetitive aspects, these technologies are a joint responsibility of academia, government, and industry.

Based on these conclusions, our recommendations are

- Technology Creation and Implementation: Precompetitive industrial technology is a vital aspect of the infrastructure needed for world-class manufacturing. Rapid advances in the quantitative, that is, mathematical and computational sciences call for continual renewal of this infrastructure. Three-way cooperation among government, industry, and academia is required to achieve success at a global level of excellence. Two excellent starting points for such cooperation would be (a) a systematic prioritization of needs of the manufacturing community for quantitative sciences and technologies and (b) collaborative work of the mathematical and computational sciences community with applied scientists, engineers and others with important roles in creating manufacturing technology. Values and performance measures (reward structure) in the academic community should be adjusted to encourage this collaboration.

- Development and Support of Management Practices: The common interests between the manufacturing and mathematical and computational sciences now extend far beyond traditional areas of statistics for experimental design and operations research for organizational design. These common interests are expanding rapidly. More effective use of mathematical and computational methods in management practices should be achieved by a two-way cooperation of industry and academia. Collaborative work of the mathematical and computational sciences community with management specialists and economic and social scientists is required. Values and performance measures in the academic community should be adjusted to encourage this collaboration.

- Education: Neither our K-12 system nor our higher-education system has kept pace with the requirements of our technology-based society. The mathematical and computational sciences community should further increase and deepen its role in reform of K-12 mathematics education and of mathematical and computational sciences higher education so that they adequately support the needs of manufacturing. The values and performance measures of the community should support the individuals who are carrying these reforms forward. Opportunities for continuing education at the interface of the mathematical and computational sciences and manufacturing should be provided both by universities and at professional conferences.

In our era of increasingly complex computing, research in the mathematical and computational sciences plays an important role in creating the new technologies and management practices of the world's leading manufacturing enterprises.

Chapter 1

Introduction

World class manufacturing and economic competitiveness are essential for our nation's prosperity and security. Today's global market affords no protected niches. Major U.S. industries face increased and unrelenting global competition. The indicators for the performance of the U.S. manufacturing sector are not reassuring (Dertouzos et al., 1989) (Faltermayer, 1990). After five years of intense national debate and many proposed solutions, trade balances have improved somewhat but are still strongly negative and optimists are limited to claims that we may have turned a corner or that by now we may only be losing ground slowly.

In the three decades immediately following World War II, a rapidly expanding economy encouraged belief in a system that was already at that time being questioned by some. In that system, the scientists made basic discoveries, the engineers and designers designed, and the manufacturers produced. Optimization of the system was achieved by optimization of individual processes and components. Quality was measured by the absence of defects. As global competition grew, the response of many manufacturers was to promote greater efficiency in the system they knew best. R&D, raw materials, and production processes were all individually optimized but the expected outcome, optimization of the manufacturing enterprise overall, was not achieved.

A new kind of thinking in manufacturing is emerging, one that engages the totality of the manufacturing system instead of dealing separately with its individual parts. Manufacturing is no longer a collection of separate, highly specialized functional units, or silos, linked in a hierarchical structure by corporate management. Today, a successful manufacturing enterprise is a complex system of interdependent processes linked laterally.

> With this expanding complexity, we need to look at manufacturing as an integrated system and optimize it as a total process, from product design to marketing, instead of

> suboptimizing on a tool-by-tool or machine-by-machine bases. We must recognize that manufacturing increasingly is driven by advances in science. (Bloch and Conrad, 1988, p. 7)

A revolution, one led by the rapid increase of computational capabilities and an increasingly quantitative approach to problem solving, is transforming the manufacturing world. The expensive and time-consuming build-test-fix and build-sell-repair cycles are being displaced by quantitative methods, which increase the chances that the product will be built right the first time it is built.

> [W]e must understand the necessity of relying comparatively less on experience and more on sound theory. The ability to apply trial-and-error learning to tune the performance of manufacturing systems becomes almost useless in an environment in which changes occur faster than the lessons can be learned. There is now a greater need for formal predictive methodology based on understanding of cause and effect. This methodology can be expressed in a variety of forms: equations, mathematical models, simulations, algorithms, approximations, etc. Of course, a good deal of such methodology already exists, but the practices of industry tend to place greater reliance on experience-based knowledge than on theory-based knowledge. This difference is due in part to the failure of practitioners to familiarize themselves with the analytical tools that are available. In part it is due to a failure of the research community to develop the kinds of tools that are needed and to put them into a usable form. (Solberg, 1988, pp. 4–5)

Computers remove humans from repetitive intellectual tasks and permit human intelligence to be applied to goals of a new level of difficulty and significance, goals that would be unattainable without computer assistance. To appreciate this statement, think of the way machines multiply the mechanical strength of their human operators by factors of thousands and more. A radical transformation in information processing has taken place because of the computer. The changes affect all aspects of information technology, including communication, storage, analysis, and retrieval. Profound changes are also occurring in the discovery, design, and processing of materials in manufacturing because computing power is now readily available. The categories in which much of modern manufacturing thinking occurs are indicative of the increasingly important role of mathematics, statistics, modeling, simulation, and computation: computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), computer-integrated manufacturing (CIM), statistical quality control (SQC), and so on. Along with nonquantitative factors, these technologies permit manufacturing industries to gain competitive advantages at both the process and the enterprise level.

There is general agreement that success in a competitive industry requires simultaneous attention to production quality, production efficiency, and satisfaction of customer requirements. Today, quality is defined as products and services beyond present needs and expectations of customers. Improved technology is part of the process for achieving these goals. Innovation is now mandatory. Accurate sensors for precision process control, modeling and simulation of production processes, robotic control, and automation contribute to production quality and efficiency at the level of unit processes. Related methodologies, applied to engineering design, lead to reduced design time. They also lead to design for quality, and design for manufacturability. Rapid concept-to-market development cycles and rapid materials-to-customized-product manufacturing cycles have a strikingly positive impact on the ability to satisfy ever-changing customer requirements. At the enterprise level, computer-integrated manufacturing, with its flatter management structures and streamlined inventory and material handling schedules, reduces production cycle time. Tools for investment analysis go beyond discounted cash flow and allow improved planning and corporate investment decisions.

However, industry is experiencing increasing difficulty justifying corporate generic precompetitive research. Because such research often cannot be successfully kept private or proprietary, due to the time lag between research and product sales, it is viewed as infrastructure, just as a network of highways and rail transport is infrastructure. Access to this infrastructure, these highways of the mind, is essential to the competitive position of U.S. industry and the future of our economy. Here, three-way cooperation involving government, academia, and industry is required.

In one economic sector, agriculture, there exists a positive model of cooperation among government, academia, and private enterprise. The support of a network of colleges and universities, the Agricultural Research Service, research institutes, and the chain of USDA extension offices provides a whole spectrum of activities from advanced agricultural, biochemical, and genetic research to transfer of basic agricultural technology to education and implementation. The results allow U.S. farmers to be among the most efficient in the world. Individual states—California, New Jersey, New York, Ohio, Texas, and many more—are playing increasingly active roles in fostering cooperation between universities and industry. Great manufacturing nations in the Pacific Rim and Europe are doing the same. Is it not possible that successful policies can be adapted to manufacturing in all of the United States?

The purpose of the present report is twofold. First, we discuss the role of the mathematical and computational sciences in making possible the competitive success of manufacturing on both the technology and the management level. Second, we identify the human resource issues that need to be addressed. In Chapter 2 of this report, we examine a series of issues in contemporary manufacturing technology and management that are being addressed by quantitative tools. In Chapter 3, the vital role of mathematics, statistics, modeling, and simulation in a number of emerging manufacturing technologies is highlighted. Chapter 4 focuses on quantitative aspects of emerging management practices. Chapter 5 discusses education of the workforce, of mathematical and computational scientists, and of managers. In Chapter 6, the conclusions and recommendations presented at the end of Ch. 1 are discussed in light of the material of Chs. 2–5.

The rapid changes that are occurring in the manufacturing enterprise and the sense of crisis regarding our competitive position have prompted a series of studies and reports. We summarize a representative selection of these reports in Appendix A. Two of these reports (Technology Administration, 1990) (National Critical Technologies Panel, 1991) have as their goal the identification of critical technologies for the future. Others focus on a single technology such as materials science (NRC, 1989b, 1991a) or high-performance computing (NRC, 1991c). Still others focus on manufacturing methods and organization (NRC, 1991b) (Gunn, 1992) (Heim and Compton, 1992). The study (Alic et al., 1992) places these issues in a broader geopolitical context. In Appendix B, areas of the mathematical and computational sciences that play important roles in manufacturing are listed.

The major conclusions of this report are:

- A revolution is transforming the manufacturing process and the organization of industrial enterprises.
- New technologies and management practices enabled by the quantitative, that is, mathematical and computational sciences are among the driving forces of this revolution.
- In their generic and precompetitive aspects, these technologies are a joint responsibility of academia, government, and industry.

Based on these conclusions, our recommendations are

- Technology Creation and Implementation: Precompetitive industrial technology is a vital aspect of the infrastructure needed for world-class manufacturing. Rapid advances in the quantitative, that is, mathematical and computational sciences call for continual renewal of this infrastructure. Three-way cooperation among government, industry, and academia is required to achieve success at a global level of excellence. Two excellent starting points for such cooperation would be (a) a systematic prioritization of needs of the manufacturing community for quantitative sciences and technologies and (b) collaborative work of the mathematical and computational sciences community with applied scientists, engineers and others with important roles in creating manufacturing technology. Values and performance measures (reward structure) in the academic community should be adjusted to encourage this collaboration.
- Development and Support of Management Practices: The common interests between the manufacturing and mathematical and computational sciences now extend far beyond traditional areas of statistics for experimental design and operations research for organizational design. These common interests are expanding rapidly. More effective use of mathematical and computational methods in management practices should be achieved by a two-way cooperation of industry and academia. Collaborative work of the mathematical and computational sciences community with management specialists and economic and social scientists is

required. Values and performance measures in the academic community should be adjusted to encourage this collaboration.

- Education: Neither our K-12 system nor our higher-education system has kept pace with the requirements of our technology-based society. The mathematical and computational sciences community should further increase and deepen its role in reform of K-12 mathematics education and of mathematical and computational sciences higher education so that they adequately support the needs of manufacturing. The values and performance measures of the community should support the individuals who are carrying these reforms forward. Opportunities for continuing education at the interface of the mathematical and computational sciences and manufacturing should be provided both by universities and at professional conferences.

Chapter 2

Contemporary Manufacturing and the Mathematical and Computational Sciences

The sweeping changes produced by computer-based and computer-enabled mathematical technologies are evident in the design and management of products, processes, and entire enterprises. These technologies are a critical aspect of competitive manufacturing. They are essential both in the incremental improvement of existing processes and products and in the creation of radically new processes and products. In this chapter, the important role of the mathematical and computational sciences in contemporary manufacturing technology and management practices is discussed. In Chapters 3 and 4, we will see that the role of the mathematical sciences in emerging technologies is even more important.

The broad field of manufacturing ranges from the very concrete (materials that go into products) to the very abstract (information management and organizational structure). There is insufficient awareness of the ways in which the mathematical sciences have assisted industry in attaining its current level of achievement in all of these areas. Statistical analysis reduces data from manufacturing processes and systems to meaningful forms. Modeling reduces manufacturing problems to quantitative relations and equations suitable for attack by algorithmic methods. Mathematical algorithms written in computer code, that is, software, express the quantitative relations and equations in a format suitable for computational solution. Hardware produces the raw computing power. The revolution that is transforming manufacturing involves notable progress in modeling, impressive improvements in software, and dramatic advances in hardware.

A few of the areas that have benefitted from the mathematical and computational sciences but that are not mentioned in this chapter are the search for raw materials (oil, metals, other minerals), the design of medical devices and equipment, including medical/biological imaging devices, and financial planning and investments. The report (NRC, 1991d) discusses critical contributions made by the mathematical and computational sciences to the manufacture of aircraft, semiconductors and computers, and automobiles.

The role of the mathematical and computational sciences in innovative technology and management practices in manufacturing is becoming larger and more central than has historically been the case. We begin our discussion in this chapter by describing how the mathematical sciences have contributed to progress in the most concrete area of manufacturing, namely, materials.

A. ADVANCED MATERIALS

Over the past decade, the design and processing of advanced materials have reached a stage where progress is difficult to achieve by trial and error. Experiments are expensive and time consuming. On the other hand, complete models based on first principles that include all of the microstructure are computationally infeasible. Development of mathematical models and computation are tools of increasing assistance to the metallurgist and materials scientist for the understanding of properties of existing materials and the design of new materials.

A new approach to modeling material properties is needed. New techniques of predicting the detailed properties of materials as a result of processing are needed on all scales: atomic (0.1 nm), molecular or subgrain (1–100 nm), grain or large molecule (0.1–100 μm), and macro (0.1 mm and up). In determining the phase transitions important in heat treatment and bulk forming (rolling, extrusion, etc.) of steel, titanium, aluminum, and other metals, the mathematical and computational sciences play an important role. Work is proceeding at all levels and, in some cases, with practical results, for example, in predicting the crystallographic texture in metals resulting from various rolling schedules and predicting the mechanical properties of various textures. Grain growth and dendritic phenomena are simulated using two-phase models. Homogenization approaches link microscopic structures and macroscopic properties.

Shape-memory alloys such as nitinol and a few other copper-based alloys exhibit unusual behavior due to changes that occur in the strain-to-stress function when the temperature is changed slightly. If a small stress is applied to a nitinol wire at a "low" temperature (for instance, room temperature), the wire changes shape very much like a plastic material; the deformed wire does not bounce back to its original shape when the stress is removed. However, when the deformed wire is heated only slightly, the material goes through a phase transition and the wire returns to its original shape. This remarkable behavior has made shape-memory material very attractive in several applications. A sleeve of shape-memory material is used to join pipes in airplanes. Nitinol wires are being used to design heat engines (Wang, 1985). (Shape-memory wires are also used in making dental arch wires for orthodontic braces.) The mathematical issues for processing high-quality shape-memory alloys focus on analyzing the microstructure and trying to predict macro-level characteristics. One thing that is known about the microstructure is that a small increase in temperature causes the large surface area of the interfaces dividing the distinct phases of the microstructure to disappear completely. Mathematical modeling will play an important role in gaining understanding of how microstructure phenomena determine the macro behavior of the strain-to-stress function.

Specific types of fine structure in crystals are of importance in certain products. Semiconductor wafers require silicon with certain crystal structures induced by ion implantation. One class of high-strength ceramics, partially stabilized zirconia, owes its toughness to a microstructure that consists of tiny second-phase particles that undergo stress-induced structural transformation. In some other advanced materials, quality is enhanced by removing microstructure, for example, microstructural defects in orientation in liquid crystals and the "twin" microstructure in high-T_c superconductors. ("Twins" are regions of alternating shear: the material shears in different directions across the interface between these regions.) The design and processing of such materials requires sophisticated physically based mathematical models. Mathematical tools and ideas from statistical mechanics, partial differential equations with rapidly oscillating coefficients, differential geometry, numerical nonlinear analysis, and scientific computing are currently being developed for these applications.

The rapidly growing area of polymeric systems, that is, materials consisting of mixtures of various polymers or of polymers in solution, presents challenging issues. To control the quality of the various products, one needs to model and simulate multiphase systems, polymer gels, rubber networks, polymer liquid crystals, colloids, membranes, and so on. By studying the microstructure, one can predict macroscopic material properties and improve the design of these materials. The rheology of polymeric suspensions plays a crucial role in manufacturing magnetic tapes, color film, and shock absorber fluids. Polymeric suspensions are modeled by the Langevin equations with appropriate external fields and interparticle forces. Simulations in which properties of these products are predicted are based on non-equilibrium Brownian molecular dynamics methods for the solution of the Langevin equations or on Monte Carlo methods. When there is hydrodynamic interaction between the particles and the fluid, the simulation is based on Stokesian dynamics.

The mathematical sciences have an impact on processes involving polymeric material in a number of ways, including prediction of structural development during processing and deformation and stress in the interim and final products. The simulation of processing flow for a polymeric fluid requires a rheological description of viscoelasticity, a subject that can be approached at different scales, depending on the manufacturing needs. For example, the polymeric flow in a coating film is modeled as a large number of individual particles in a solution interacting according to the Langevin equations. Further mathematical research is needed to simulate routine processes such as liquid-phase polymer processing operations under conditions of practical interest.

New ceramics with exceptional strength and hardness are finding increasing use in electrical and magnetic products. They find application also in high-speed machining, automotive parts, and aerospace components. Sintering and creep in ceramics manufacturing is an area that requires kinetic modeling at both the atomic and mesoscopic scale. Monte Carlo simulation for spin models and finite element procedures are of great assistance in predicting damage formation during sintering, creep, and crack growth. The information thus gained allows restructuring the process to avoid these phenomena.

Nonlinear optical (NLO) materials are used in instruments that manipulate laser beams, equipment to protect from radiation, all-optical switching devices, and soliton-based optical fiber communication networks. NLO materials must be manufactured with precise nonlinear refractive indices. Models that reflect the interaction among various physical mechanisms of nonlinearity are currently used to find transient solutions in fast switching regimes. Manufacturing high quality optical fibers from silica glasses requires an understanding of the distortions caused by higher-order terms in the nonlinear Schrödinger equation. To predict the properties of photorefractive materials, organic and polymeric, one must study the propagation of nonlinear waves in nonlinear waveguides. Practical methods for preventing "optical breakdown" can be designed by insight gained from mathematical models that exhibit wave collapse. Optical radiation damage can be predicted or prevented by applying the insight gained by studying mathematical models. Properties of nonlinear optical materials are the subject of the report *Mathematical Opportunities in Nonlinear Optics* (NRC, 1992c).

This brief review of advanced materials shows the wide range of mathematical models and tools that have been contributing to improved product technology. The report *Application of the Mathematical Sciences to Materials Science* (NRC 1991a) describes more fully the range of mathematical disciplines used in designing and analyzing advanced metals, solid crystals, electronic and semiconductor materials, nonlinear optical materials, polymers, ceramics, glasses, and biomolecular materials. As the demand for advanced materials with higher levels of performance grows, the need for mathematical models and computational algorithms will increase.

B. MANUFACTURING PROCESSES

Manufacturing processes can be improved through analysis, modeling, and computer simulation. They can also be improved by the use of data from the manufacturing process itself, analyzed by the statistical method of experimental design. There is a strong need to integrate these two approaches, as simulation and modeling depend on manufacturing data for their validation, while statistical data analysis is more penetrating when it utilizes an underlying physical model. Statistical approaches are presented in this chapter in Sec. D. In the present section, we emphasize the modeling and simulation approach.

The quantitative understanding that results from modeling and simulation of processes allows one to improve manufacturing tolerances and reduce rejection rates. Also improved is the ability to diagnose and solve manufacturing problems as they arise. Modeling a process is a step toward modeling its control, to be followed by optimization and automation of the process. Each of these steps typically improves quality, while reducing error rates and cost. To illustrate these points, we describe below various manufacturing processes, including microelectronic, molding, crystal growth, casting, joining, curing, and coating processes. The mathematical models for these processes are differential, integral, and discrete equations with and without memory.

The manufacture of semiconductor material requires understanding the process at the atomic level. For example, molecular beam epitaxy (MBE) and ultra-high vacuum chemical vapor deposition (UHVCVD) techniques now allow deposition of monolayers of atoms. The need to investigate surface structure and interface behavior at the molecular level should renew interest within the mathematical community in quantum theoretical approaches.

The manufacture of integrated circuit "chips" involves many processes. Chips are made on silicon or, occasionally, gallium arsenide wafers. These wafers are discs 8 to 20 cm in diameter and a few millimeters thick. On each wafer, many rectangular chips with side lengths between 0.1 mm and 1 cm will be produced. On each finished chip, there are up to one million "devices." A common procedure for laying out the devices on the chips consists of the following "photolithographic" steps: (1) a thin layer of the silicon is oxidized, (2) that layer is coated uniformly with a material called photoresist that is sensitive to light, (3) the wafer is covered by a patterned mask and is exposed to ultraviolet light (or, for very small devices, an electron beam), (4) the photoresist that is exposed to the light (or the electron beam) "develops," that is, it polymerizes and hardens, (5) the unexposed areas of the photoresist layer are washed away leaving the silicon dioxide layer bare, (6) the bare portions of the silicon dioxide layer are then etched out down to the silicon substrate by a hydrofluoric-based acid that attacks neither the hardened photoresist nor the silicon, and (7) the hardened photoresist is stripped off. The devices are developed in the places where the silicon dioxide was removed. The scattering of light (or electrons) in step (4) has been modeled by the ill-posed backward heat equation, which leads to difficult numerical problems (Gerber, 1988). Etching has been modeled by (Kuiken, 1990) as a moving boundary problem. Masks are built by analogous lithographic processes on larger geometric scales.

To achieve the desired isolation of the devices, the regions between them must be oxidized to a deeper level than in the initial oxidation. This process has been modeled in (Chin et al., 1983) as a system of elliptic equations coupled through boundary conditions on a common free boundary. Each device has a source, a drain, and a gate. Titanium silicide is deposited over these three regions in order to produce a high quality electrical contact. The titanium silicide growth causes some warping, as modeled in (Willemsen et al., 1988) and the references given there; it involves "nonlocal" boundary conditions on several moving boundaries. One needs to solve all of these equations in order to determine the "I-V" curve, which depicts how the unavoidable variability in the manufacturing process affects performance. Further mathematical analysis is required to bring the models closer to the operating conditions in wafer fabrication rooms.

With circuit geometries on chips becoming increasingly complex, the processes for manufacturing chips require more careful modeling and design. For ion beam etching of semiconductor wafers, the narrowness of the line width is a primary measure of quality. Design and manufacturing faults limit yields in chip production, especially for the newer high density circuits. Procedures currently in use in chip fabrication fall into the class called "microfabrication" or "micromanufacturing," that is, the fabrication and manipulation of materials on the scale of a micron. Microfabrication processes include lithography, etching, deposition, epitaxial growth, diffusion, implantation, optimization of movement of equipment, testing, inspection, and packaging. Integrated circuit applications with a focus on thin line width are currently the main area of micromanufacturing but thin films and surface treatments (diamond films, for example), and micro-mechanical devices (microsensors and micromotors) are of growing importance.

As the dimensions of the lines, films, and devices decrease further below the micrometer range, one speaks of "nanomanufacturing." Nanomanufacturing is an important technology for the manufacture of devices, mainly quantum semiconductor devices, that have line widths with characteristic dimensions on atomic scales, that is, 10 nm or less. The fabrication of nanometer-thick films and surface treatments, for example, diamond films, is also considered nanomanufacturing. Nanomanufacturing extends the techniques of micromanufacturing (such as ion beam lithography) to the nanometer scale; it is a "top-down" approach in which the challenge is to form smaller and smaller devices while retaining enough control over structure to permit proper functioning. In contrast, molecular manufacturing is a "bottom-up" approach that aims to build complex structures by exploiting molecular-mechanical techniques for guiding atoms and molecules to form materials and structures in which each atom or molecule occupies a specified location. Extension of the techniques of micromanufacturing to nanometer scales has had considerable success but one cannot avoid certain thermal and kinetic constraints that become more important as the dimensions of the devices become smaller. The bottom-up approach of molecular manufacturing (see Sec. D of Ch. 3) is becoming an attractive alternative.

In the manufacture of fiber-reinforced plastic composites, a dense fiber mat is introduced into the mold. A plastic resin is then injected into the voids between the fibers. The equations governing the flow of the resin through the fiber mat are similar to those used for enhanced oil recovery (Darcy's law, miscible displacement). For this displacement process, the flow is stable. Nonetheless, small voids remain in the composite due to fluctuations in the local permeability of the mat. These voids are a source of structural weakness. Analysis of flow patterns during molding can relate void formation to variation in fiber-packing densities as well as to wetting angles and injection-rate flow velocities. Such analyses thus suggest strategies to reduce voids. Computations based on front tracking numerical methods have reproduced the phenomenon of void formation and are being used in the analysis.

Phase transitions are important in a number of processes, including the growth of high quality wafers from a substrate, casting of alloys, and welding to join metals. Equations for dynamic growth of a phase boundary allow analysis of stable and unstable (dendritic) growth regimes. In the case of alloy casting, dendritic finger growth during solidification can yield nonuniform casts with diminished strength. Mathematical modeling helps diagnose and avoid these problems during manufacture. Modeling of welding allows precise and economical control of robotic welds without waste from over-engineering of tolerances. Heat curing and bulk forming (for example, rolling or extrusion) of metals may involve a dynamic phase transition. Crystalline microstructure and lattice imperfections are added or removed at this stage, with important consequences for material strength and toughness. Since the transition occurs in the interior of the metal and sensors monitor only surface temperature, simulation is of assistance in determining the proper curing schedule.

Films and coatings are subject to a ripple instability if flow velocities during manufacture exceed a critical threshold. This phenomenon is analyzed and proper methods for its control are obtained through modeling and simulation of appropriate differential equations. In the same way, processes involving sprays, combustion, plastic extrusion, abrasion, etc. can be understood and refined using quantitative methods.

C. PROCESS CONTROL

Controls are ubiquitous in manufacturing. A chemical manufacturing facility may contain thousands of individual controllers. They regulate temperature, pressure, and input product streams. They ensure the quality and efficiency of the process and may guarantee its safety as well. We describe several areas in which control theory is important and in which advances in mathematical control theory can lead to improved products.

In the 1970s and 1980s, engineers used linear approximations to model processes and the controls to guide them. This linear control approach is adequate for processes that operate near a fixed equilibrium state or in which there is not much interaction between the various inputs (for instance, in an assembly line of independently manufactured parts). It is, however, inadequate for processes in which there is highly nonlinear interaction among the input variables, such as in many chemical reactions. The linear control approach is never adequate when the process has no steady (equilibrium) state about which to linearize the model. When the linear control approximation is replaced by the more adequate nonlinear system, the control is referred to as a nonlinear control, even when the control variables themselves appear linearly in the system. Nonlinear control for manufacturing is an area that holds considerable promise for progress.

To model and control chemical process manufacturing, one first prepares a global synthesized model in the form of a flowsheet, a diagram that describes the plant equipment and its interconnections and the transformations that occur in the various subsystems where the chemical processes take place. Once a flowsheet configuration is determined, simulation software is used to find parameters for optimal plant design and nonlinear process control.

Many chemical manufacturing processes in operation today were designed or modified with the help of in-house or commercial software packages. The equation systems arising from the processes generally consist of material and energy balances, equipment sizing and costing equations, and physical property equations (for example, vapor-liquid equilibrium correlations). Also included are unit model equations (for example, kinetic equations for a chemical reactor), flowsheet connection equations describing the process topology, and design specification equations (setting the purity of the product stream, for example). The equations involved in these various steps include partial differential equations with nonlinear reaction terms describing the chemistry, Navier-Stokes equations describing the dynamics, and conservation laws for compressible flows. The equations often contain time delays and integro-differential terms. Of course, a number of parameters or control variables need to be chosen so as to optimize the performance. The result is a highly nonlinear control system, usually with distributed parameters (spatially nonuniform flow variables), stochastic noise, and other complicating features. In order to control the process parameters in real time, one must develop more effective mathematical models and improved computational algorithms.

Batch reactors involving nonlinear chemical processes are an example where mathematical modeling has been successful. Polymerization reactors have highly nonlinear dynamical characteristics. Laboratory processes have been developed in which nonlinear control of temperature is applied to a continuously stirred tank polymerization reactor (Soroush and Kravaris, 1992). Distillation columns are a class of batch reactors in which singular perturbation techniques have been used to analyze and nonlinearly control the chemical processes. The results have been incorporated into a feedback control law (Levine and Rouchon, 1991) and the procedure has been successfully implemented on the depropanizer at the Elf Aquitaine refinery in Donges, France.

Metal processing provides another example where mathematical modeling has been successful in controlling nonlinear processes. Metal processing involves several steps: reduction (smelting and refining), composition and properties control (alloying, quenching, heating, and annealing), and forming (casting, forging, rolling, extrusion, and drawing). Control plays a major role in improving performance at each of these steps. Some of these processes use the same mathematical methodology as the chemical processes described above; others share the methodology that is described in Sec. A on advanced materials. We concentrate here on one aspect that is unique to metal processing, namely, ideal metal forming or, briefly, ideal forming. The metal is modeled as a rigid, perfectly plastic material. As it is deformed, the relative positions of the crystal atoms are altered by the applied external pressure. One seeks to control the process so as to (i) minimize the total work and (ii) maximize the homogeneity of the deformed material. Minimizing the total work avoids excessive shearing (which weakens the material). The concept of the ideal forming process originated about 30 years ago with the realization that, if a rigid, perfectly plastic strip can be reduced by steady plane-stress processing in such a fashion that a principal stress direction coincides with the material streamline at every point of the plastic zone, then the process is just as efficient as simple plane-strain compression. It was shown at U.S. Steel (Devenpeck and Richmond, 1965) that the desired result could be achieved by the use of frictionless dies of sigmoidal shape. Here the control variable is the shape of the die. Since then, other two-dimensional and axially symmetric ideal flows have been achieved by optimal design of the dies. However, the three-dimensional problem is still unresolved. Partial solutions of this control problem lead to nonlinear degenerate elliptic systems and to nonlinear hyperbolic systems (Chung and Richmond, to appear).

Sheet metal forming in many industries, the automobile industry in particular, provides another example in which control theory and optimal design play a major role. One would like to provide predictive tools for the design and control of the stamping processes and the selection of sheet materials. The metal sheet, initially flat, is stretched over the die by a punch with curved edges. The goal is to construct the shape of the punch and the die so as to achieve a final desired surface without damage to the quality and shape retention of the metal. The constitutive laws involve stress-strain relations with hardening. Boundary conditions, including those that represent lubrication of the die, are important in this context. Numerical (finite element) methods have been very successful. See (Cavendish et al., 1988) and the references therein.

There is an increasing amount of literature on feedforward/feedback control of single input/single output (SISO) nonlinear systems with large disturbances. Feedback control is designed to minimize the error or variability in the performance of a system. However, if we want the system to follow a prescribed plan, then we need to augment the feedback control with feedforward control. A typical case is that of robot manipulation (Goor, 1985). For a discussion of feedforward controllers for chemical processes, see (Daudidis and Kravaris, 1989) and the references therein. To make these models effective, one needs to develop numerical methods that are faster than real time, so that the control variables can be manipulated in real time. The control theory needed includes not only classical techniques but also more recent tools based on differential geometry, Lie algebra, and singularity theory for dynamical systems (Sussmann, 1983).

D. STATISTICAL QUALITY IMPROVEMENT

There are three statistically based strategies for ensuring quality: (a) quality assurance, (b) quality control, and (c) quality improvement. Quality assurance, a traditional way of ensuring quality, consists of sampling the final product and rejecting it (or the entire batch) if the defective parts exceed a certain percentage. This procedure is not efficient because errors are not detected until the end of the manufacturing process, after much work has been expended.

Classical statistical methods for quality control employ response surface methodology (Myers, 1971). The response surface is often taken to be quadratic; statistics are used to fit the coefficients of the quadratic with the sampled data. Optimal and robust engineering design for complex industrial processes are being addressed by high-dimensional statistical modeling. One class of techniques involves statistical visualization of the data with a sequence of color pictures. A second class of techniques creates a parametric model for each stage with a prior distribution for each of the unknown parameters; the data are then used to estimate sequentially the posterior distribution associated with each state of production. As the process runs, parameters are determined and, at the same time, the maximum value on the surface, the "point" at which the process is optimized, is sought (Box, 1969).

The term quality improvement is used to describe the improvement of the operation by the elimination of the cause of errors. To accomplish this, one must have appropriate quality performance measures in place. Until recently, quality performance measures were typically based on or related to cost, which led to less-than-optimal identification of causes of errors in processes and production. Cost-based performance measures, discussed below in Sec. E, are increasingly being supplemented by operations-based performance measures (Ch. 4, Sec. A).

Often, a critical factor in improving quality is decreasing statistical variability, that is, increasing consistency. The Japanese engineer Taguchi was one of the foremost promoters of the concept of reduced variability in manufacturing. His "parameter design for experimental design" approach has generated a great deal of interest among quality practitioners and statisticians. The Taguchi approach is, however, not appropriate for processes in which interactions play a large role. Interactions may not play a major role in production with parts that are manufactured independently of one another. They do, however, often play a key role in chemical processes. For processes with significant interaction between subprocesses, other methodologies are under investigation (Nair, 1992). The issues involved are experimental strategies, dynamical systems, and the role of interactions.

In evaluating data, one often assumes statistical independence. But independence can not always be assumed: tools become dull or wear out, so that one must develop models with dependent sampling (Spanos, to appear). Time series methods are being used to address this problem. Kalman filters and other statistically based filtering procedures can be used to extract reliable information from noisy process data (Crowder, 1986). One direction of emerging interest is the study of rare events, such as power or plant failure, ecological disaster, etc. Here, direct Monte Carlo simulations are wasteful. On the other hand, asymptotic estimates based on probability theory may provide quick answers of sufficient precision (Weiss, 1986). Questions such as how to control the time of rare events are beginning to be addressed on the factory floor.

Reliability theory is another aspect of statistical quality improvement. As production lines become more complex, so do the models used to monitor and sustain these production lines. In (Lin et al., 1990) and the references therein, some interesting mathematical problems for homogeneous asymptotically reliable serial production lines are described for a modular paint shop at an automobile assembly line. Reliability models are used in design and simulation of flexible manufacturing systems.

Most work by statisticians does not directly include the physics and chemistry that underlie the processes and that often make the processes interactive. Some recent work, however, has begun to take account of the physics and chemistry, at least in a phenomenological way (Vander Wiel et al., 1992). Including a good description of the physical/chemical processes leads to a better choice of response function and to useful information on the nature of the statistical parameters that need to be determined (Myers, 1971). Some recent work in this direction, with applications to batch polymerization and production of electric components, is described in (Faltin et al., to appear). The general methodology is called Algorithmic Statistical Process Control (ASPC). It requires initial process assessment, model formulation, processing data, model fitting and evaluation, control rule development, monitoring procedure development, and on-line implementation and assessment. Each of these steps has a mathematical basis. For example, model formulation requires defining the process in terms of differential equations if the process is continuous or in terms of discrete equations if the process is discrete. In many cases, the linear models assumed by statisticians can be viewed as Taylor-series approximations of more complex physical laws, thus paving the way for future research on nonlinear regimes. Many products are now routinely designed with the aid of mathematical/computational models. Given the inputs—designable engineering parameters and parameters representing manufacturing-process conditions—the model generates the product's quality characteristics. The quality improvement problem is to choose the designable engineering parameters such that the quality characteristics are uniformly good in the presence of variability in processing conditions (Welch and Sacks, 1991).

E. COST-BASED PERFORMANCE MEASURES

Cost-based accounting, including the analysis of variances from standard costs, had its origin in the scientific management movement of 1890–1910 (Kaplan, 1989). Cost was used at that time, and is still now used, to estimate product prices, to establish the level of profitability of the enterprise, and to measure and control performance inside the enterprise. In a more or less static system of mass production, cost had a major role in optimizing the use of direct labor and machines and it was for tracking of individual worker and machine efficiencies that the accounting systems were tailored.

At the present time, cost-based performance measures still have a role to play at the production stage when direct labor is a large portion of the cost. They are important for financial summaries for shareholders and government. Since the early 1900s, however, revolutionary changes in the ways in which products are designed and produced has resulted in a dramatic decrease in the percentage of direct labor and machine operating expenses in the cost of most products and in an increase in the percentage of overhead. Although more and more intricate methods for assigning overhead to products were devised, it was found that traditional cost-based systems were not conducive to measuring quality and encouraging quality improvement (Kaplan, 1990). As automation proceeds, the percentage of direct labor in the cost of products will continue to decrease.

Various improvements in cost-based accounting are in use or are being developed (Sakurai, 1990). Target costing establishes goals or targets for costs of parts and activities by working backward from a market-based price using return-on-sale percentages. Activity-based costing (ABC) attempts to trace overhead costs, such as those of supervision and quality control, to specific products; more complex products that require additional attention by supervisors and quality control personnel will typically receive a larger share of the overhead. Activity-based accounting in the electronics industry, in which direct labor is an extremely small portion of total costs, is described in (Foster and Gupta, 1990). This new system incorporates cost drivers based on complexity of products and efficiency of the production process and can provide information on trade-offs among complexity, functionality, cost, and other factors (Kaplan, 1989, 1991) (Banker et al., 1990).

Modeling and simulation will be increasingly important factors in developing these systems. Developing cost accounting systems that are tailored to improving specific areas of the design/production process and/or can locate primary drivers of cost is an area of research that will require the cooperative efforts of survey specialists, accounting specialists, mathematical modelers, and statisticians.

In the future, cost-based performance measures will continue to be used. However, they will be only one category of a wide spectrum of measures that will be available to the manager as data on which to base decisions. The other measures on this spectrum will be operations-based performance measures, which are discussed in Sec. A of Ch. 4.

F. BENCHMARKING

Traditionally, goals for quality, cost, and productivity have been established using historical standards, often ones internal to the enterprise. Goals such as a 3% decrease in cost and a 2% increase in productivity vs. the previous year were the norm. Benchmarking is a system and a practice that extends the process of goal-setting by systematically seeking industry-best practices and establishing them as operating targets. The industry-best practices that are sought are not necessarily those found in the same type of manufacturing as the enterprise under consideration. They are practices of any organization that are related to the practices of the enterprise under consideration. Over the past decade, benchmarking has become an element promoting quality essential for success in the global marketplace, one that counteracts the usual effects of cost-based accounting systems.

Once a specific product or process has been chosen for benchmarking, data is collected from direct contacts, visits, and public and private data banks. Companies with the best analogous product or process are identified. As described in (Camp, 1989), when Xerox initiated competitive benchmarking in 1979, it found industry-best practices not only among its competitors but also at L. L. Bean (for warehouse operations), GE (for information systems), Deere (for service parts logistics), Ford (for assembly automation), and the Federal Reserve System (for bill scanning).

At present, the data collection step of benchmarking is often done by a combination of "manual" and computer searches. Questionnaires, customer surveys, and site visits provide much information. Annual reports, public databases, databases of professional and trade associations, and trade publications are skimmed to identify relevant data. Computerized database searches using key words help rationalize this process but often provide too much, too little, or erroneous information because of the inability of the searching procedure to "understand" what it is looking for or to distinguish the slightly different meanings attached to the same words in different databases.

The ways in which the mathematical and computational sciences are contributing to rationalizing the benchmarking process are many. Scanning technologies, based on recent research in statistical character recognition and already available in commercial products, permit articles printed on paper to be "read" electronically. Graph theory, an area of discrete mathematics, is used to develop efficient search procedures for large, structured databases. Automatic language-processing procedures that can scan databases and text and "understand" the material improve "targeting" of the search. Statistical procedures for combining information from sources with different quality and quantification levels assist in more accurate identification of the companies with industry-best practices.

The role of the mathematical and computational sciences in benchmarking, as in the other areas of manufacturing mentioned in this chapter, is an important role, one that needs to be exercised in collaboration with many areas of applied science, engineering, the natural and social sciences, and corporate decision making.

Chapter 3

Emerging Manufacturing Technologies

Many of the areas of contemporary manufacturing mentioned in Chapter 2 are undergoing rapid evolution. In the present chapter, we focus on six emerging manufacturing technologies, in which the developments resemble revolution rather than evolution. The first two of these technologies, intelligent machines and solid modeling, are basic technologies that underlie other emerging manufacturing technologies. Rapid prototyping, molecular manufacturing, and biomanufacturing are technologies that did not exist ten years ago but that are expected to be major factors in the manufacturing world ten years from now. Environmentally benign manufacturing is an emerging technological area that is becoming a way of life and will have profound influence in all areas of manufacturing.

A. INTELLIGENT MANUFACTURING

Intelligent manufacturing requires intelligent machines and integration of these machines into manufacturing processes that can sense the state of production and automatically take or recommend appropriate action. An intelligent machine is a machine a) with instrumentation that "knows" ("senses") the state of the process, b) that "knows" a model by which the future evolution of the process can be reliably predicted, and c) that possesses a control mechanism by which a desired end state of the process can be achieved at an acceptable cost. With intelligent machines, efficient and flexible manufacturing is possible:

(i) One can manipulate different components needed to continue the process as desired.

(ii) By changing some of the parameters, one can quickly manufacture a different version of the product.

(iii) If a fault occurs, it is detected immediately rather than at the end of the process.

(iv) To improve a product, one can easily look at each stage of the process and identify those parameters that need to be changed.

In order to achieve intelligent manufacturing, we need both new tools and a high level of coordination in the following areas.

(a) Sensing: Machine vision and other types of sensing are becoming important features in manufacturing. Applications include reconstruction of surfaces, segmentation, non-destructive testing, pattern recognition, and texture recognition. Pattern matching from a predetermined set of templates is helpful in controlled environments. Machine vision is important in inspection of integrated circuits (ICs), printed circuit boards, and lead bonding for microelectronic chips. Automatic wafer inspection has only a limited ability to detect erroneously printed wafers because circuit patterns on wafers that have already undergone several stages of processing appear in an unpredictable variety of color and texture. But machines may still be able to "see" and "see through" texture variation better than human eyes. Machine vision algorithms will require the mathematical tools of stationary spatial stochastic processes and Markov random fields. Currently, the models on which the sensing procedures are based are not sufficiently sophisticated or robust and the numerical schemes that predict system behavior on the basis of information from the sensors are too expensive or too slow. With better sensors and more processing power becoming available, new mathematical ideas and more powerful numerical algorithms will be the key to advances in this area.

Computer vision has seen recent important mathematical developments (Geman and Geman, 1984) (Mumford and Shah, 1989). The model in (Geman and Geman, 1984) assumes a Bayes rule and converts the sensor output into a posterior distribution. The model in (Mumford and Shah, 1989) is based on variational principles and incorporates deep mathematical results from geometric measure theory. Edge enhancement methods based on shock capturing ideas show promise (Osher and Rudin, 1990). Neural nets provide another approach to edge detection and other pattern recognition problems.

Computerized tomography (CT) and ultrasound for nondestructive evaluation (NDE) are important sensor technologies. Increased sensor accuracy can be achieved by mathematical research in signal processing for more effective deconvolution algorithms based on modeling of the sensors themselves. Increased algorithm speed is obtained by vectorization or parallelization of the algorithms. New mathematical basis functions, in particular, wavelets, are being used for image compression and algorithm acceleration (DeVore et al., 1992).

Sensors and, especially, "microsensors," for temperature, pressure, and chemical characteristics require extensive mathematical modeling. For many microsensors, ordinary or partial differential equations for complex physical processes that take place inside the sensor must be solved to ensure proper calibration and accuracy.

(b) Motion and Robotics: Motion sequences to describe mathematically the paths that tools take are required in both hard and flexible automation. Robot manipulation in manufacturing is increasingly based on mathematical models and software. The models include (i) open link robot manipulators based on Lie groups of rigid motion and (ii) motion planning and inverse kinetics based on methods from classical algebraic geometry, computational geometry, and dynamical systems. An opportunity exists here for mathematicians with a background in dynamical systems, control theory, and computational geometry to work with electromechanical engineers to develop motion control languages. Fuzzy logic, that is, logic that is based on imprecise quantifiers such as "large", "few," "almost all," "very small," and so on, is the basis for some robot control systems that are increasingly able to represent human reasoning. "Seeing" shapes and sizes of objects and avoiding stationary and moving obstacles are tasks that can be accomplished by autonomous robots with fuzzy control. The challenge in designing a fuzzy controller is in tuning it properly, a task that requires additional mathematical research. Neural nets is one among many mathematical techniques being applied to tuning fuzzy controllers (Schwartz and Klir, 1992).

(c) Efficient design and process representation: Intelligent design tools include CAD, CAE, CAM as well as specific programs controlling the flow of raw materials, distribution of tasks, and service and repair schedules. Representation (modeling) of processes is the issue discussed in Sec. B of Ch. 2. For many purposes, such as real-time design and control, complete modeling, even when feasible, is not practical; computations based on complete models are often too slow for an interactive CAD tool (as, for instance, in chemical processes and in VLSI). Efficient real-time computation is often obtained by table look-up, with recomputed solution trajectories tabulated in terms of convenient basis functions. Important understanding may be gained by modeling a simplified process. An intelligent machine is able to "understand" the data supplied by the sensors, predict the future evolution of the process using the models, and adjust its motion or actions to keep the process close to the desired position or state.

B. SOLID MODELING

Solid modeling is an essential step in rapid prototyping, robotics, and other areas of manufacturing where unambiguous descriptions of solid objects are required. Solid modeling grew rapidly during the 1980s and is poised for explosive growth in the future. Solid modeling is used in numerical control (NC) program verifiers for detection of collisions and in design of robotic motion. In the design of prototypes, solid modeling is currently used for making incremental improvements in designs close to completion but, due to speed and complexity limitations, it is not used in earlier phases of the design process. In the near future, solid modeling is expected to become the dominant medium for describing parts and products in the mechanical industries. Solid modeling will drive CAM modules and assist in generating NC programs. The growth will center around increasing the speed of the algorithms, the complexity of the objects that can be modeled, and the ability to include complex tolerancing information (not just maximum deviation but also information on the shapes and roughness of allowable deviations) in the model.

The solid modeling frameworks under development or in current use include

1) feature-based modeling, in which objects are modeled in terms of functional elements (bosses, holes, slots, etc.), each of which can be represented by a small number of parameters,

2) sweep representations, in which objects are determined by the volume "swept out" by a surface or solid moving along a trajectory,

3) cell representations, such as octrees (the three-dimensional analogue of quadtrees), in which objects are represented by a union of uniform or non-uniform cells,

4) boundary representations, in which solids are represented by two-dimensional surfaces and by indicators that specify the side of the surface that is the interior of the object, and

5) constructive solid geometry (CSG), in which objects are described by Boolean combinations (unions, differences, and intersections) of various simple solids (cubes, rhomboids, conic sections, etc.).

These modeling systems are described in (Hoffmann and Juan, 1992) and (Voelcker, 1988); of these five systems, the latter three are mature. Cell representations are expected to play an important role in the accelerating attempts to interface engineering design with analysis (Brunet et al., 1991). Sweep representations are relatively undeveloped and continue to pose many research problems regarding degeneracies, accuracy of approximation, and data volume. They are important in robotic motion planning and NC machining.

Feature-based modeling is a promising area that has arisen over the past decade. Feature-based representations are convenient for design because there is a direct association of features of the object with elements of the geometric representation. Integrated feature-based systems of design for manufacturability that combine feature refinement, process selection, tool selection, process sequencing, fixture planning, and NC cutter path generation are currently under development. Feature-based representations can include tolerance information.

Replacing piecewise planar approximation methods common in many systems by exact sculptured-surface capabilities is an important goal in solid modeling in general and feature-based modeling in particular. How best to locate and represent intersections of sculpted surfaces is under investigation. Blending, that is, connecting different features by patches that satisfy certain surface curvature constraints, is another important area under development (Bien and Cheng, 1991). Much of the research on this subject concentrates on developing the mathematics of the patches without consideration of the constraints implied by the topology of the surrounding solid boundary or those arising from edge connectivity. Research that takes a more global point of view is needed.

C. RAPID PROTOTYPING

Rapid prototyping (the automated manufacture of a specified three-dimensional shape directly from computer instructions) is currently under development. Rapid prototyping has as its goal the acceleration of the design process along with an increase in the reliability and manufacturability of the design. Rapid prototyping requires integration of software tools and languages with electromechanical output.

Prototyping begins with the conceptual description of the product. A geometry language and editor provide the means for conceptual description in a given solid modeling framework. This language should be shared with the CAD tools of engineering design. When properly integrated into the geometry of the CAD tools, this language enhances their usefulness. Recent progress in areas related to applications in manufacturing include design for assembly, shape matching, mesh generation, surface approximation, and feature identification. Automatically reproducing or "reverse engineering" the shape of an object, for example, a prototype, with only the object as input, is a basic task that requires further research. Machine vision and solid modeling, discussed in the two previous sections, are important tools in reverse engineering.

Visualization is the next step in prototyping. For simple parts, current three-dimensional graphics with rotating frames, adjustable viewing perspectives, and illumination sources are adequate. However, for complex assemblies, resolving compatibility (freedom from collisions, etc.) of the various parts and subassemblies is a challenge. Virtual reality, a tool now being developed, will be useful in analyzing and designing complex assemblies and in determining a valid assembly sequence for robotic implementation. With virtual reality, the design engineer will be able to float or crawl, in computer simulation, through the interior of the assembly, such as an airplane wing or automotive engine, and resolve dangerous tolerances or discover space remaining for utilization.

Production of computer specified output is the final stage of rapid prototyping. For computer chips, commercial fabrication facilities are already capable of automatic production of custom design chips directly from computer-based specifications.

Many of the techniques of rapid prototyping are based on layer deposition. In stereolithography, a support plate is suspended just below the surface of a vat of liquid polymer. As a laser beam (UV or visible light) traces out the geometry of the particular section of the solid part, a thin layer of polymer reacts to the radiation by solidifying in the exposed areas. The support plate is then lowered (by as little as 0.001 inch) until the new solid polymer section is just below the surface of the polymer film and the geometry of the next section is traced by the UV laser. The process is repeated, layer by layer, until the entire prototype has been constructed. Other techniques of rapid prototyping include fused deposition modeling (FDM), in which a numerically controlled extrusion head builds the prototype, again layer by layer. In this case, a solid part section is built by depositing a thin stream (0.001 inch diameter) of melted material (polymer, wax, etc) onto the support tray with the appropriate geometry of the part section. After completion of the section, the support tray is lowered and construction of the next layer proceeds. Another prototyping technique under development involves laser sintering. In this method, a thin layer of material particles (polymer, wax, ceramic, metal, etc.) is deposited on the support tray, As in stereolithography, a laser beam, controlled by a computer with a three-dimensional solid model of the object to be manufactured, passes over the material and, in this case, fuses the particles in its path. The support tray lowers, a new layer of material particles is deposited, and the process continues.

Development of rapid prototyping techniques requires further mathematical research to find optimal ways of modeling complex structures. Minimal path algorithms are important in designing equipment for rapid prototyping. Excess movements do not merely waste energy and time; they also result in loss of accuracy and in reduced repeatability. Prototypes produced by any of the current methods require either cooling or curing before they are ready for use. These processes can produce imbedded residual mechanical stresses, which reduce the accuracy of the final object as well as its useful life. The dimensional accuracy and structural integrity of the final prototype can be improved by annealing procedures developed using mathematical modeling and computer simulation of the stresses.

Rapid prototyping concepts are a basis for the flexible manufacture of simple parts with short manufacturing runs. They can be considered as a manufacturing technology in their own right, for the production of essentially unique products. They also have important applications beyond manufacturing. For example, CAD and rapid prototyping are under consideration for forensic reconstruction. Also, anthropologists are interested in 3D graphics and construction of 3D models. Research will assist rapid prototyping in realizing its very promising potential in manufacturing and other areas.

D. MOLECULAR MANUFACTURING

It is important to distinguish between molecular manufacturing, which is the manufacturing of atomically precise structures, and nanomanufacturing, which is the manufacturing of structures that are on the scale of 10 to 100 nanometers but where the placement of individual atoms is statistical in nature. Lithography can produce nanoscale structures but it is unlikely that it can produce structures in which the location of each atom is specified. Molecular manufacturing seeks to use molecular mechanics to position molecules, guiding chemical reactions to create products with atoms and molecules in precise positions.

Molecular engineering is highly mathematics-intensive. The mechanical and electronic properties of atoms, molecules, and materials are calculated and the results are used to design structures with the desired properties, such as quantum semiconductor devices (quantum "dots," "wires," "wells," and "boxes"). Monomolecular layers of optically sensitive materials such a rhodopsin that have high switching speeds are under investigation as data storage devices. Molecular engineering techniques to create zeolite with channels tailored to adsorb specific molecules are being developed to enhance the performance of catalytic converters in automobiles (see description in Sec. F, Environmentally Benign Manufacturing, in this chapter). In these areas, full molecular modeling and simulation are much more efficient than experiments for narrowing the range of options in the design phase.

Molecular manufacturing is qualitatively different from nanoscale manufacturing and involves radically different manufacturing concepts. Research in molecular manufacturing is unusual in the history of technology in that mathematical and computational methods for analyzing device behavior are available before the tools needed to construct the devices have been developed. In other areas of technology, the mathematical and computational sciences have provided either 1) a general scientific basis that assists in creation of devices chiefly in indirect ways or 2) methods for analyzing the behavior of devices designed on the basis of other knowledge. For molecular manufacturing, however, the mathematical and computational sciences also provide methods for exploring the range of possible devices, selecting objects to guide initial experimentation and development.

Today, semiconductor devices can be manufactured in which the arrangement of atoms is precisely controlled in one dimension. As atomically precise control is extended to all three dimensions, a quantitative leap in capability will occur. One long-range goal is to build large structures of precisely placed atoms for use as computing devices. A view of the capabilities of molecular manufacturing and how these capabilities can be developed is given in (Drexler,1992).

E. BIOMANUFACTURING

Until the 1980s, living organisms (microbes, animals, and plants) were bred for desirable characteristics that occurred as a result of natural variation among individuals of a species. The procedure for identifying factors that resulted in desirable characteristics utilized classical statistical procedures of the design of experiments. Increased rates of mutagenesis were achieved by application of radiation or other mutagenic agents. Natural and induced mutation were slow but, over the long term, powerful agents in tailoring species to specific needs. In the pharmaceutical area, for example, the level of penicillin production has been increased by a factor of more than 10,000 since World War II by natural and induced mutation and selection.

With the advent of modern molecular biology in the 1980s, genetic engineering became the primary tool for creating organisms with specific characteristics. Genetic engineering allows two advances beyond the traditional techniques. First, genes can now be easily moved between distinct species (for example, human to bacteria). Second, if the product of the gene is known, changes in the biosynthetic capability of a cell or organism receiving the gene can be manipulated in a predictable, predetermined manner. Thus, characteristics of organisms can, in principle, be assigned and reliance on random variation to breed organisms with specific characteristics is not necessary.

The largest impact of genetic engineering so far has been in the production of therapeutic proteins in factory processes using bioreactors (currently about $4 billion in annual sales). Production of chemicals and biopesticides using genetically-modified cells is becoming a reality. Improved plants (for example, ones with virus- or herbicide-resistance) and animals are in advanced development. Organisms for treatment of hazardous wastes are being developed. Gene therapy to treat human disease is being explored.

Knowledge of genes and of the structure and function of their products is the "raw material" of biotechnology. Genomic mapping is only slightly over 10 years old. Complete genomic information—requiring the listing of millions of nucleotides—will soon be available for bacteria, yeast, and a nematode. Statistical science assists the laboratory scientist in designing the experiments, in the analysis of the data, and in the construction of the map itself. Analysis of the coiled, supercoiled, and knotted three-dimensional structure of DNA requires locating active genes that are involved in protein coding and inactive genes and noncoding segments that are not. Identifying a gene of 500 units spread out in small segments along 10,000 or more units of DNA makes use of combinatorics, statistics, geometry, low-dimensional topology, neural nets, mathematical programming algorithms, and extensive computations. Two quantities from differential geometry, twist and writhe, turn out to be helpful in explaining the linking number of a DNA double helix. Knot polynomials and tangle theory are used to determine the mechanisms and products of recombination of DNA. The fundamental roles of these mathematical technologies in genomic mapping are described in (NRC, to appear).

One of the basic technologies needed to support genetic engineering is database technology. Information on the millions of nucleotides in genes must be parsed, stored and retrieved in usable forms, forms in which individual characteristics can be identified and comparisons with multitudes of other genes can be made. Relational databases, that is, databases in which each datum is stored with information about how it relates to the other data, are being used. Object-oriented databases, in which data are stored in classes that possess some common characteristics such as functions or connections to other objects, are also used. These types of databases are based on mathematical results in graph theory. Special data description languages and query languages are used to store and retrieve information from these databases. In all of these areas, the work has only begun. Research on novel structures for massive databases will enable progress not only in biomanufacturing but also in solid modeling, benchmarking, and numerous other areas of importance to manufacturing.

The design and optimization of biomanufacturing processes would benefit significantly from complete models of the intrinsic population dynamics of cell cultures. Improved techniques to solve large sets of nonlinear differential equations or, in some cases, integral-differential equations are needed. One aspect of molecular biology is the study of the flow and control of information. Better cellular models coupled with techniques from the information sciences will yield deeper insights into regulation and differentiation in cellular systems.

F. ENVIRONMENTALLY BENIGN MANUFACTURING

Increased predictive knowledge to support decision making under environmental constraints is required. Modeling, simulation, and statistical data analysis are essential in designing manufacturing processes that have minimal negative impact on the environment. They are also essential for measuring the actual effect of the process, and, if necessary, redesigning the process. Given the burden that remediation of pollution places on the manufacturing enterprise, the alternative method, that of trial and error, is too expensive. It is far more costly to clean up pollution than to prevent the pollution in the first place.

Manufacturing enterprises already spend considerable resources meeting current constraints on CO_2, SO_2, and NO_X emissions. Expanded future controls on emissions and a free market for emissions permits will put market forces behind reduction of emissions. Plans for reducing harmful gaseous, liquid, and solid chemical byproducts of manufacturing processes are often based on mathematical modeling and simulation that suggest minimally expensive alternative processes.

Manufacture of automobile emission control devices is an area where understanding of chemical processes by quantitative methods is of prime importance. As pollutant gases flow out of the engine, they pass through a catalytic converter and undergo a chemical process in which they are converted to relatively harmless gases. The process, which involves several chemical species, is affected by temperature, which satisfies a partial differential equation coupled to the reaction rate of the species. The largest amount of pollution occurs at a cold start. One would like to raise the initial temperature (viewed as a control variable) so as to minimize the emission of hazardous gases during the warming cycle. The nonlinear partial differential equation control problems that occur in catalytic converters have been studied numerically (see (Oh and Cavendish, 1982) and the references therein) but the models so far are only one-dimensional. Research on higher-dimensional cases is needed.

The case of pesticides and agricultural chemicals further illustrates the need for improved modeling and simulation. Manufacturers of these chemicals use simulation models to predict the time of biodegradation of the chemicals in relation to the time for dispersal in the environment. These models test many statistical combinations of rainfall, soil composition, and application schedules to ensure, for example, that the chemical will be inactive before it reaches the water table. Alternative pesticides that target specific pests and are either not harmful to other organisms or degrade quickly into harmless substances are designed by a combination of experimental methods, statistical design of the experiments, statistical analysis of the results of the experiments, and first-principles computational chemistry simulations. Finally, virus- and pest-resistant plants that require no or little agricultural chemicals are being developed by genetic engineering, as mentioned in Sec. E above in this chapter.

For many chemicals, and especially biochemicals, the relevant reaction rates are not known with sufficient precision. Simulation methods are useful in determining reaction rates from more easily measured data and in assessing the uncertainties resulting from underdetermined physical or geological parameters in the models. Methods for large-scale simulation are needed to resolve multiple length scales. The effect of nonlinearities in the reaction equations is not sufficiently well understood. The statistical influence of atmospheric turbulence and geological heterogeneities on dispersion and transport is an area of active research.

Modeling and simulation are used to predict the effect of new facilities on the environment. For example, in the construction of a cooling channel for an electric generating plant in southern Italy, the effect of lowering the water table and the possible incursion of salt water from adjacent coastal areas was studied prior to the decision to proceed with the project (Rangogni et al., 1992). When planning cooling facilities, the effect of excess heat on the environment must also be taken into account. Water used for cooling in electric generating plants and in factories must often be discharged into lakes and rivers at temperatures above the natural temperature of the environment. One seeks to install the intake and discharge and to schedule the discharge so as to minimize the adverse effect on the biological environment. Mathematical optimization has a large role in determining a system that not only protects the environment but also minimizes capital and operating costs.

The same methods of modeling, simulation, and statistical data analysis that are needed to design minimally polluting processes are the methods used in remediation of pollution that has already occurred. A "pump and treat" remediation method for polluted soil is normally designed on the basis of simulation models. Well planned treatment that assures that air, clean water, or bioremediation nutrients flow to the places where the pollution is most severe can result in lower cleanup costs.

Experience has also indicated that environmental safety of the product may be as important as safety of the manufacturing process. Recent statistical studies by the Rand Corporation illustrate this fact. These studies have shown that human exposure to a number of common pollutants is more likely to result from interior household sources than from airborne pollution, even in urban areas. Redesign of products to reduce or eliminate exposure often depends on substitution of materials and may use mathematical/computational methods discussed in Sec. A of Ch. 2.

Mathematical modeling and optimization of environmental impact vs. manufacturing cost helps eliminate under- and overengineering, both of which increase overall direct cost and may produce undesirable byproducts.

Chapter 4

Emerging Management Practices

A new model for management practice and organization of a manufacturing system is arising. The model is based on decentralization, with increased resources and authority becoming available to employees at the lower levels of the structure. It is based on integration, with distinct functional units communicating transparently and working and planning interdependently. It entails expanded access to information and increased use of quantitative methods, which enable these changes and support decision making by managers. Quantitative methods and tools for management supplement, but do not replace, the traditional humanistic approach to management decisions.

Taken as a whole, the above changes reduce middle levels of management and flatten the institutional hierarchy. These changes narrow the gap between those in control of institutional leadership, product development, and strategic decision making and those responsible for the production and delivery of the product.

Quantitative tools for management integrate many aspects of the manager's responsibility. Operations-based performance measures supplement accounting tools in deciding on resource allocation. Financial planning that allows a flexible response to future uncertainty and variability can be given a quantitative basis. Integration of essential but "incompatible" databases is a necessary step in the optimization of overall enterprise performance. The analysis of product and process alternatives, which may previously have been carried out mainly on the basis of engineering models, can now be extended to include non-engineering management criteria, such as financial, taxation and marketing considerations. With the increasing complexity of the criteria that must be balanced, there is an increasing need for quantitative methods to provide the manager with the "systems" view that he/she needs to make correct decisions.

Management practices will continue to depend in essential ways on many nonquantitative social and humanistic factors not subject to analysis or modeling. At the same time, the mathematical and computational sciences will play an increasingly important role in complementing those factors.

A. OPERATIONS-BASED PERFORMANCE MEASURES

The shift from a slowly changing marketplace to a rapidly changing marketplace has been the driving force behind the move away from traditional cost-based performance measures. In the manufacturing establishment of the future, oriented toward fulfilling in minimal time the divergent demands of a variety of customers, a performance measurement system based on traditional cost accounting will be a distraction at best and a detriment at worst.

> According to a recent survey of manufacturing companies co-sponsored by the National Association of Accountants (NAA) and Computer-Aided Manufacturing—International (CAM-I), 60 percent of the executives polled expressed dissatisfaction with their firms' performance measurement systems. In the electronics industry, where both manufacturing and market environments have changed most, 80 percent were dissatisfied. (Dixon et al., 1990, pp. 22–23)

The basic tasks in the coming global economy are to increase quality and to respond to customers. In this framework, cost is rightly viewed not as a driver but rather as something that is driven by other factors. Full utilization of worker and machine time, which is encouraged by cost-performance measures, while a laudable goal overall, can be detrimental if the products produced consume valuable resources and cannot be sold because they do not correspond to the needs of the customer. Cost-based performance measures typically cannot distinguish between good and bad product designs. Cost-based performance measures systematically devalue or undervalue short cycle times, the "no-repair" benefit of built-in quality, inter-unit cooperation, and the option value (flexibility value) of knowledge and research. Cost-based performance measures are useful only when they are applied along with operations-based performance measures. Narrowly focused cost-based performance measures are one of the factors that discourage integration of the enterprise.

> [M]any of the problems for the manufacturing sector started when maintenance and servicing of the product were established as separate profit centers, creating a unit that is expected to be evaluated like other profit centers and to provide a return on investment. Making a profit on product design errors or on the lack of product reliability does not provide a strong incentive to improve customer satisfaction. (Bloch and Conrad, 1988, p. 8)

Operations-based performance measures to promote quality improvement and flexibility as well as customer satisfaction include:

- Design and development: number and magnitude of successful new systems developed, number of unique product features, development lead time, comparison of actual results with plans, percentage of sales consisting of new products, the extent to which new products require subsequent modifications, measures of product standardization (proportion of off-the-shelf parts)

- Production and production scheduling: manufacturing lead time, setup time, changeover time, processing time, total throughput time, period-to-period variation in output rates, defective items produced, scrap produced, rework rate, first-pass yield (items completed without rework being required), obsolete products produced, age of equipment, repairs to machinery, inventory levels, on-time delivery, missed sales

- Human resources: support of employees for corporate policies, employee turnover, lost workdays

The performance measures chosen by the enterprise should be measures that encourage corporate goals such as higher quality, flexibility, time-based competitiveness, and customer satisfaction by drawing attention to non-value-added or negative-value-added activities. Continuous improvement will necessitate continual changes in the measurement system. New goals will be established as a result of benchmarking (see Sec. F of Ch. 2) and these goals too will require new measurement systems.

Inexpensive computing power and the mathematical and statistical algorithms and software that make use of this power are a key to creating performance measurement systems for many corporate goals. As the enterprise articulates additional goals and related performance measurement systems with greater levels of refinement, the need for sophisticated database technology will increase (see Sec. B of this chapter). Various types of recently developed statistics are needed to set up non-biased sampling procedures to produce the measurements. Traditional statistics, such as regression analysis and analysis of variance will be used to obtain information from some of this data but these methods will not be sufficient in many cases.

Use of operations-based measures leads to fundamental issues in the statistical area called combination of information (also called pooling of information, meta-analysis, and data fusion). While cost-based measures are easily aggregated to produce performance measures of the factory, the division, and the enterprise, most operations-based measures are not easily aggregated. Vertical integration of process data to produce data for units and, eventually, data for overall performance of the enterprise is a complex problem in combination of information similar to that faced by federal agencies that must integrate data from many different sources to produce aggregate numbers on the performance of the national economy. There is intense ongoing research in statistics that already provides partial solutions to some of these problems (NRC, 1992a). How to combine non-cost-based and cost-based measures to create an accurate picture of the overall health of the enterprise remains a challenging problem. A high-level "scorecard" based on many operations-based measures and a few financial measures is discussed in (Kaplan and Norton, 1992). Hierarchical models for obtaining aggregate performance measures for the whole enterprise and exchangeability analysis for determining trade-offs when the performance data to be compared are "incompatible" are two areas in which research is proceeding.

B. COMPUTER-BASED INFORMATION MANAGEMENT

Information management refers to the set of techniques and technologies that store, reference, analyze, transmit and interpret data. Information management has become a new technology essential for manufacturing. In fact, it is regarded as a strategic weapon in manufacturing competitiveness (Morton, 1991). The importance of information systems in manufacturing was recognized in the 1960s but recognition of the magnitude of their importance has increased significantly with time. If information is in the database, information management lies in the understanding, analyzing, and optimizing of multiple databases, the means of accessing them, the communications among them, and the data processing needed to refine their contents so that manufacturing decisions can be made on the basis of the information.

Today, manufacturing is moving toward a batch quantity of one, that is, toward individual manufacturing of different items. For some years now, the major automobile companies have been able to deliver to the customer a car with a unique combination of features chosen from a large set of options. The ability to do this is a technical, logistical feat. The current practice at Porsche is to consider all cars as essentially special orders (Noppen, 1991). All parts, procedures, and information necessary to build the custom car from thousands of parts and millions of options must arrive virtually simultaneously for the process to be successful.

Traditionally, information management in support of manufacturing has centered on maintaining databases of inventory, production schedules and capabilities, customer orders and delivery schedules. Recently this list has begun to expand. Now many other factors, including work in progress, are tracked as inputs to software that schedules production lots and supplies immediate quotes on price and delivery lead times to customers. Operations-based performance measures should be included in the enterprise-wide information system so as to enable people at every level of the enterprise to assess their own performance and to understand the impact of their performance on the achievement of the objectives of the enterprise. As the enterprise articulates further goals and related performance measurement systems with greater levels of sophistication, the need for massive database technology will increase.

Current support includes the maintenance of information about the geometry, manufacture, and assembly of the components that make up the product. This type of data is more difficult to manage than traditional data, due to the complexity of data types and interrelations. Specifically, methods of data organization, storage, and query have become difficult issues for the management of geometric information. Additionally, the desire to integrate other types of information developed during the design process further complicates the situation. The design process defines what is to be manufactured; decisions made based on geometric considerations and performance simulations are important.

However daunting the current challenges, future information management needs will require modeling, statistical, and database capabilities beyond those now realized. Some of these needs can be understood by viewing manufacture as one aspect of the concurrent engineering process.

Concurrent engineering is a systematic approach to the integrated concept-to-market development of products and their related processes, including manufacture and support. This definition of concurrent engineering requires giving a structure to the product development process and requires support of team communication. Thus, to develop quality products, concurrent engineering requires the structuring of communication among the people participating in the product development process (design, manufacturing, marketing, sales, maintenance, training, etc.). There are three fundamental ways in which this communication must be structured: (a) the communication must take place among people, programs and databases; (b) the communication must facilitate team activities and enhance information sharing; and (c) the communication must naturally generate a history of the development of the product to support manufacturing, reporting, and redesign. Such a history is necessary to provide traceability and accountability for decisions made during the product development process.

The main components of a concurrent system are: (a) a database structure that allows representation of engineering information generated during the product development process, including the specifications, proposed designs, and product and process descriptions from the perspectives of design, manufacture, marketing, maintenance, and training; (b) a collection of tools for structuring the product development process to enable data capture and to support team decision making; (c) a collection of tools for transparently entering information into the database, including free-hand sketch capture tools, text editors, and interfaces to computer-aided tools (CAD, CAM and CAE), spreadsheets and analytical tools (e.g. variational, parametric, finite element, and optimization); and (d) a collection of tools for browsing and extracting information from the database.

Typical manufacturing operations in a moderately large, FORTUNE 1000, company may depend on 600 to 1000 different databases. Some are functionally organized, for example, by department. Others are cross-functional, such as those containing manufacturing and requirements planning files. Many of these databases need to interoperate. For instance, the file of orders interacts with and must therefore be consistent with the purchasing file. Not all files need to interoperate, which reduces the interaction complexity from an n^2 interaction to one of smaller dimension. Current manufacturing practice requires subcontracting functions to tens or hundreds of other companies, often situated internationally. Boeing's more than 3000 suppliers for the new 777 airplane is an extreme case. These companies also have databases numbering in the hundreds. The number of interacting databases could then conceivably number in excess of a million. The complexity of the interactions between the databases and the necessity of ensuring appropriate consistency in such a large system needs mathematical investigation. The problem is complex just due to cardinality; the key issue of maintenance of semantic consistency across and among subsets of the data system further increases the level of complexity.

Of more serious moment is the fact that databases come in several flavors. There are the old sequential databases found in systems of 1960s and 1970s vintage, and the current network, relational, object, and knowledge bases. Increasingly, systems contain databases in the format produced by a particular piece of software such as EXCEL or LOTUS. The language of databases is mathematical logic, sets, and relations. The database can consist of numerical data, predicates such as "the color of the car is red," or data needed for calculating the stress on a part by finite element modeling. It may contain image and video data. In addition to predicate calculus, higher-order logics such as nonmonotonic and temporal logics are needed and used for some applications. For example, it is important that planned and unplanned changes to a product be time-stamped and tracked. In this way, they can be unrolled, so that the appropriate maintenance can be performed or regulatory compliance ensured. There is much current interest in active databases that incorporate agents that perform autonomous tasks according to a script or set of commands embedded in a command language. In the database field, this idea appears as a mediator, which assists in the semantic translations needed for interactions among disparate databases. It is important to understand the mathematics of agents and their languages (Shoham and

Tennenholtz, 1992) and to make adjustments so that not only will the actions resulting from them be predictable but the entire society of interacting agents will be stable. The agents must not oscillate or run away, causing a production halt or other economic catastrophe similar to the Wall Street problems caused by computerized trading.

Some of the work described in the prior sections of this report deals with issues in the mathematical modeling of particular domains, plastic injection molding and sheet metal forming, for instance (see Secs. B and C of Ch. 2). The issue in information management of the manufacturing enterprise is that the semantics used in modeling in one local domain are often not exportable to an adjacent domain that requires the results of that modeling: information on the modeling method and the environment for the design of the process is often not available for operational control of the process. There are usually only islands of semantic congruity where information sharing is possible. Modern manufacturing demands wide, endemic sharing of information for optimal operation. What is needed is that information be made available across islands in consistent ways without incurring the expense of n^2 two-way translators between the islands.

Another challenge is to ensure that the deep mathematical results found in the simulations and analyses done in the islands of information are not lost. We need a theory of simulation in which we can combine symbolic reasoning, abstract models (for example, partial differential equations), discrete event simulators, and real parts and processes in a consistent manner. The framework must be able to answer questions at a given abstract level with abstractions at the same level but derived from data at all levels. This is unknown territory today.

Other issues in information management in manufacturing lie in security and information system optimization. The world is rapidly being wired up to work at gigabit communication rates. Today companies can transmit information to each other but wide sharing is not common. Companies will interoperate within the limits of trust and security in order to maximize profit and minimize the leakage of proprietary information. Secure information transfer is based on the mathematical area of cryptography. Several levels of protection for corporate information transfers are needed, each with a level of confidence appropriate for the transactions being conducted. As communication, whether secure or not, via shared databases becomes the operating norm, performance considerations will cause data to be migrated to locations providing fast access to local queries. Optimization of information systems will involve designing adaptively distributed databases. Databases will become adaptively distributed in ways that the original designers did not envisage. The mathematics of migration and, more importantly, upgrade and deletion in the distributed system, needs examination.

The just-in-time (JIT) revolution deals with the delivery of parts to the manufacturing process at the right time and in the correct format. It is essential to realize that information must also be supplied just-in-time so that parts and products can be processed properly. Automata theory may be useful in discovering and elaborating the next operating paradigm beyond JIT.

The future support of information management puts demands on the mathematical and computational sciences in many areas:

- database systems capable of supporting incomplete, nondeterministic multi-language data

- integration of information that is represented graphically, textually, and numerically

- visualization of databases

- translation of information (solid-modeling databases, production databases, etc.) from system to system (different CAD systems, factories, etc.) without loss of format

- computational optimization and simulation with abstract, nondeterministic, and incomplete information

- interactive methods of team and management decision support

- congestion control in interactive networks

- cryptology and secure/reliable communication

- Fault tolerant routing and design: research in permutation networks and non-blocking networks.

In summary, information management provides data in the correct form at the correct time for decisions to be made and action to be taken. This is done today by brute force. Sharing is often possible only within semantic islands. The challenge is to design consistent and convergent information systems that bridge the islands so that the future manager can ask questions and obtain answers without having to walk through every department in the factory.

C. FLEXIBLE MANUFACTURING SYSTEMS

Increasing manufacturing flexibility is a key to improving market responsiveness when there is uncertainty in the demand for future products, as is increasingly the case in many areas of manufacturing. New product flexibility, that is, the ability to go rapidly from concept to sale, is important. Multiple connections across functional units as well as flattened organizational structure are critical to this type of flexibility. Production volume flexibility has long been a corporate goal in cyclical industries and in businesses with high sales variances. Input mix flexibility, that is, the ability to produce the same product with different mixes of raw materials, labor and/or capital, is important. Throughput flexibility, that is, flexibility that allows the facility to continue production in spite of partial blockages due to machine failure, absenteeism, or unscheduled changes, is often critical. Output mix flexibility, the ability to build different types of products profitably in the same manufacturing plant by minor rearrangements of the production line, confers major competitive advantages. Most importantly, flexible manufacturing requires flexible people with expanded job definitions to carry out and direct the manufacturing.

Optimal design of systems with flexibility, optimal scheduling of those systems under numerous constraints, and rapid rescheduling after changes in parameters or constraints are critical for the success of the enterprise. The addition of the goal of flexibility to the enterprise results in optimization problems with greatly increased complexity. No longer do inventories buffer production from internal or external disruptions. The buffer, if it can be called this, is now the flexible production process itself. The system must now be monitored in real time, often using statistical techniques, to identify problems as they occur.

Systems theory has traditionally been concerned with modeling phenomena by differential or difference equations for continuous variables (deterministic or random). There is, however, an increasing need for dynamical models of systems the states of which vary in discrete sets and are characterized by symbols rather than numerical values; these symbols change with the occurrence of events that can also be described in non-numerical terms. The discrete events may represent start or completion of work on a part, a buffer size, failure or repair of machine, etc.

Typically the range of choices is so large that a systematic, computer-based approach is nearly essential. Operations research is concerned with these questions. A number of operations research tools have been developed, including combinatorial optimization, stochastic modeling, queuing theory, and discrete event systems (DES) modeling. DES models are in growing demand in areas such as microelectronics, automobiles, and aircraft, in which discrete components are manufactured. Even continuous processes, such as chemical processes, are often modeled and regulated by discrete controllers. Since DES illustrates the contributions to manufacturing of operations research as a whole, we discuss several issues from this perspective.

Automobile assembly involves a host of optimization problems within the DES framework. The different options offered to customers are so numerous that the vehicles produced each day in a given automobile plant are effectively manufactured individually. Under such conditions, optimization of tasks and sequencing of vehicle production are major challenges. Some heuristic strategies are described in (Yano and Rachamdergo, 1991) and the references therein but complete answers have been obtained so far only for simplified models. Mathematical tools need further development in order to provide effective strategies for assembly line and production schemes.

The direct modeling of DES leads to a very large space of events. The event space grows exponentially with the number of states. Symbolic approaches, which assist in ordering and simplifying the processes, are often used to gain understanding. Symbolic approaches are particularly effective if there are only a few quantities of great interest, for example, the times for completion of certain tasks. One can then try to construct approximations that give quick answers to questions like "Can task x be completed in time t when symptom y is observed at time *s*?" Such an approximation can be constructed by reduced-order models or by aggregation of variables.

JIT is another DES area of great importance. Ensuring just-in-time arrival of parts in the right sequence is a discrete optimization problem of great complexity, one that is already being addressed. Queuing theory plays an essential role here. Optimal arrangement of stations in facilities, balancing of production in assembly lines, and planning of production lots with breakdowns of machinery, require further research in optimization, graph theory, and statistics.

Many models of manufacturing systems are hybrid models that contain equations in continuous variables (for example, differential or difference equations) and DES models (Varaiya and Kurzhanski, 1988) (Inan and Varaiya, 1989). A need exists to develop consistency at the interface between the continuous and discrete equations. Better techniques to handle the noise need to be developed, a topic for researchers in stochastic approximation. Although many of the models are locally convex, they are often not smooth, either because of the nature of the model or because of noise. Optimization of nonsmooth functions is an active area of mathematical research (F.H. Clarke et al., 1989).

Flexible manufacturing systems are intimately connected with other aspects of the enterprise needed for world-class manufacturing capability. Information systems to provide the data for optimal scheduling must be in place. Performance measures that encourage flexibility must have been instituted. The enterprise must choose investments that support flexibility. Finally, the organization must function in an integrated manner to make use of its flexibility.

D. CAPITAL BUDGETING FOR FLEXIBILITY

Internal resource allocation and capital budgeting in a large company that has several thousand capital projects to evaluate each year have a large impact on the success or failure of the company. Traditional capital budgeting procedures based on discounted cash flow have serious shortcomings as decision tools. Discounted cash flow measures often overlook the value of higher quality and lower cycle time. They make delaying investment attractive because they do not take into account the cost of catching up with competitors (Kaplan, 1991). They usually do not recognize the value of a decision to innovate in advance of the competition (Baldwin, 1991) and are not sufficiently refined for planning optimal resource allocation in a global economy. They systematically undervalue the option value of investments. This option value, as with put and call options in the stock market, derives from an intrinsic variability of business factors (foreign exchange rates, market preferences, new technologies, etc.). Recently, it has been realized that capital budgeting should involve techniques similar to those techniques of mathematical finance theory that have become important in program trading. Due to the variability, there is a value (over and above that determined by discounted cash flow) in options that allow flexible response to future developments.

Techniques from mathematical optimization, stochastic modeling, and DES are already in use for making investment decisions. United Airlines, with a continuing stream of turbine blades to repair, was faced with the choice between a job shop and a remanufacture facility. These two alternatives were evaluated based on computer simulation using DES methods. The favored alternative was implemented and, when completed, performed in accordance with the DES predictions. Once full production was achieved, computer simulation using ongoing production statistics allowed optimization of operations.

Investment in facilities that have high productivity but little flexibility may make sense in stable, high-volume markets but not in rapidly changing markets, such as aerospace, where a typical lot size is 100. An enterprise in a fast-changing, unpredictable area of manufacturing will often articulate flexibility as a corporate goal, that is, it will recognize the value of building into its system freedom to take various options. But flexibility must be bought at the cost of greater capital investment and, occasionally, lower productivity for individual products produced by the system. In determining how much flexibility is desirable in a given enterprise, a systematic analysis of cost/benefit ratios is useful. It can be shown that neither the totally flexible nor the totally inflexible solution is optimal. In the former case, investment is underutilized and flexibility is wasted, since variations in market line are seldom extreme. In the latter case, investment in fixed facilities is underutilized due to variation in the product mix. Optimization studies (Andreou, 1990) have shown that there is a desirable limit for flexibility and that investments beyond that limit produce insufficient return. Since future market demands are random variables, a strategy for manufacturing flexibility can be modeled as a stochastic system. One is then able to recommend on the basis of mathematical analysis which added flexibility would be most profitable (Sethi and Sethi, 1990). Further development of stochastic modeling for the analysis of flexible manufacturing is needed.

The "location" problem—where the enterprise should locate its fabrication, assembly, R&D, and other units—is solved by modeling and standard techniques of operations research. The parameters and constraints in these models are costs of capital, labor, and transportation as well as currency exchange rates, taxation, and political stability. In the competitive economy of the future, the "relocation" problem—ongoing changes in the location of various units of the enterprise to take advantage of new production options, market opportunities, and so on—will be of great interest. Instead of the previous "location" models (which were designed for slowly developing markets), time-dependent "continual relocation" models will have to be used for optimization. Setup costs, which could previously be ignored because they were one-time costs, will be factors in these models. Research on dynamic network optimization and leveraging large geographical databases with map-based interfaces is needed. Global location and relocation dynamics in the context of the complete product life cycle are described in (Phillips and Spindler, 1991).

Probabilistic planning for distribution systems, reducing mismatch and bias in personnel assignment, and decision making under conditions of incomplete information about the actions of competitors, who do not always act rationally, require further research in statistics, optimization, DES, and non-cooperative game theory.

Research and development of new products and processes in manufacturing is an area, the value of which is almost exclusively an option value (Andreou, 1990). An enterprise incurs considerable risk by delaying or not pursuing investment in research and development of new technologies.

> One obvious error occurs when managers develop the base case or "do-nothing" alternative. Invariably, analysts predict that even without adopting a new technology investment they will enjoy a continuation of the status-quo—today's selling prices and market share—into the future. Evidence from a large number of industries has revealed that companies that do not maintain their technological

> leadership will, in the future, have to absorb lower market share or lower pricing margins, and frequently both. Thus, the correct base-line forecast for the status-quo alternative of rejecting new technology investments will be some annual percentage decline in net cash flows in the future years. Henry Ford said, "If you need a machine and don't buy it, you pay for it without getting it." (Kaplan, 1991, p. 214)

E. INTEGRATED MANUFACTURING

Integrated manufacturing means the coordination of all units in the enterprise to accomplish corporate goals. Integrated manufacturing involves operations-based performance measures to encourage integration, computer-based information management systems to enable integration, flexible manufacturing systems to stabilize the integration, and enlightened capital budgeting to support the integration. All of these topics have been discussed above in this chapter. In the present section, we discuss one remaining aspect of integrated manufacturing: software systems that tie together some or all of these areas.

Computer-based information systems that transfer appropriate data and analysis among all units of the enterprise are essential for integrated manufacturing. Software for enterprise-wide data collection, data analysis, and decision optimization must be designed and implemented. The traditional approach of analyzing the enterprise-wide system as the sum of its basic components—design, production, marketing, maintenance—may have been a good model when the interactions between the components were not significant. That is, however, no longer the case, and the enterprise must be understood as a nonlinear, highly interactive system. In nonlinear systems, the complexity of the system increases exponentially with the number of elements. The result is radically increased requirements for large-scale software modules that support enterprise-wide planning and operations.

Mathematical modeling and simulation for the management of large enterprises should proceed on a much more cautious basis than mathematical modeling and simulation for materials and processes. The modeling and the input data on which such simulations are based are often only partially correct and may utilize information that is poorly quantified. The input data, the conceptual models, and the algorithmic or quantitative expression for these models are potential sources of error and must be subject to systematic validation.

How then should the models and software based on those models be used responsibly? One way to proceed is as follows. First, install the diagnostic and analysis part of the software and ensure that it is working and validated through use in the target manufacturing systems. This step is basically one of developing performance measures, discussed in Sec. A of this chapter. Then the software should be "field tested," that is, used for test projections that can be validated using other information. Continued validation and monitoring during initial use ensure that a new software tool can be introduced in a manner free from serious negative consequences. Finally, the intrinsic limitations of the software must be understood by its user.

Software systems for integrated manufacturing are gradually being developed. They will eventually become interactive, distributed systems of enormous size and complexity. Automatic generation of software for use in CIM is a major issue. Debugging of software will continue to be done by manual tools, such as using independently verifiable modules to create larger codes. Eventually, software verification, at least in cases where the logic for the model can be clearly identified, will be carried out also by intelligent testing and error-recognition procedures (Chung, to appear). These procedures will fall into two categories: 1) formal methods, which view software as a symbolic manipulator and rely on logic and 2) model checking, which automatically queries the software and checks the answers provided by the software (E.M. Clarke et al., 1992). In many procedures, algebraic methods are used to decompose the problem into smaller modules. Many procedures have the major drawback of being unable to handle the exponential state space explosion. However, heuristics in protocol validation have been greatly improved and the feasible sizes of applications far exceed what many people expected only a few years ago.

Chapter 5

Education and Training

With flatter organizational structures and more inter-unit coordination, employees at all levels of the enterprise require greater technical understanding and communication skills. Workers and supervisors on the manufacturing floor, corporate managers, design and production engineers, and scientists in research and development laboratories need to develop skills that promote optimal functioning of the manufacturing enterprise. In this chapter, several critical areas where improvement in skills is needed are highlighted.

A. AN EDUCATED WORKFORCE

While the industrial workforce was previously able to function well with basic skills, new technologies are now redefining upward the term "basic skills." Taguchi calls for workers to use simple concepts in statistics, including the statistical method of experimental design, in order to diagnose and solve production related problems in work groups on the factory floor. The position of machinist or assembly-line worker is evolving into a technical position in which numerical, statistical, and computational skills are important in keeping automatic machining tools and/or robots performing properly. The secretary in a factory is evolving into an information manager. For the workforce, literacy in basic mathematics is second in importance only to literacy in language as a fundamental goal of the educational system for a world-class manufacturing nation.

The increasingly quantitative aspects of many jobs require not just basic mathematical skills but also higher-level skills in flexible problem solving and, most importantly, the ability to learn. Unfortunately, the mathematics skills of U.S. primary and secondary school students have stayed about the same for decades, well below skills of students in nations with which we compete economically. Students of all other industrialized nations did better than U.S. students in international comparisons a decade ago and the gap has grown wider since then. In teaching and measuring, we must place more emphasis on problem solving and multi-stage reasoning. We must teach students how to cope with the quantitative problems that they will meet in the manufacturing world and in our technological society in general. Unfortunately, tests like the National Assessment of Educational Progress currently in common use stress basic mechanical skills (arithmetic) rather than problem solving.

Mathematical skills identified by one engine manufacturer as being required for various shop floor jobs were

- Basic arithmetic, including dimensional analysis, ratio, and proportions
- Algebra, geometry, perimeters, and volumes
- Trigonometry
- Statistics, including bar graphs, histograms, normal curve, mean, median, mode
- Reading of and computations for blueprints

Not every job required all of these skills, but all of them were required on the factory floor. In the future, most arithmetic operations will be done by computers. To make sense of computations, the user will have to understand the meaning of various mathematical procedures rather than just have the ability to perform the procedures mechanically. This will require higher-level approximation skills to estimate whether the answer produced by the computer is reasonable or whether input data or the parameters should be checked.

The report *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989) of the National Council of Teachers of Mathematics provides a widely praised blueprint for revitalizing K-12 mathematics education in the U.S. and proposes a school curriculum that addresses the mathematics needs of this country's workforce of the 21st century. The NCTM Standards have been endorsed by most professional societies of mathematical scientists and natural scientists and by corporate and political leaders. The Standards make far greater intellectual demands on students in all grades. In high school, they emphasize exploratory, multi-stage problem-solving activities and give extensive attention to the application of the mathematical sciences in practical real-world settings.

The number of new workers with basic mathematical skills is decreasing (NRC, 1989a, 1990) partly because the group of 16-to-24-year-olds that has been the traditional source of new workers in manufacturing industries is shrinking and will continue to shrink through the year 2000. Thus it is vital to implement the NCTM Standards as quickly as possible, so as to maximize the fraction of high school graduates ready to be productive members of the workforce. The alternative is a large increase in on-the-job remedial education.

B. HIGHER EDUCATION

While the emphasis for the workforce in general is on basic quantitative skills that permit the employee to participate in the decision-making process more directly and to make a greater contribution to the enterprise, the emphasis for technical/scientific personnel is on broadly based experience and communication skills, which they need in addition to good technical background. For managers, there is a complementary need for increased technical background in addition to broad experience and communication skills.

For mathematical sciences majors seeking industrial employment, the requirements are also increasing. The latest recommendations of the Mathematical Association of America (MAA, 1992) for mathematical sciences majors encourage more options with an applications-oriented focus, including coursework in differential equations, mathematical modeling (incorporating case studies), discrete mathematics, and probability and statistics. Courses in scientific computation, especially of the types needed in industry, could be added to this list. There is a need for more work-study and internship programs for mathematical sciences majors.

While the pool of domestic students interested in pursuing technical subjects, including the mathematical and computational sciences, is declining, there are some positive developments. Minority student scores on the Scholastic Aptitude Test (SAT) have been improving, and the gap between women's and men's performance on the mathematics SAT has closed (ETS, 1989a, 1989b) (L. Friedman, 1989). These trends carry special weight since Caucasian males will comprise only 15 percent of the net additions to the labor force in the next decade (Hudson Institute, 1987). It is a fact that SAT scores are lower than they were a generation ago and remedial mathematics instruction in colleges and universities has increased by 150% over the past 20 years (CBMS, 1992) but these negative trends are explained by the large increase in students with weaker academic preparation now attending college, a desirable development.

The term "professional" master's degree refers to a graduate degree that is not merely a preparation for a PhD. To complete a master's degree that is a step toward a PhD, a student is required to complete many theoretical courses as the basis for future research work. When the objective of the master's program is to produce graduates ready to take on responsible positions in manufacturing as well as business and government laboratories, a curriculum more cognizant of applications and professional development is appropriate. Currently, the master's degree is a valued degree in various areas of statistics, operations research, and scientific computing. The Board on Mathematical Sciences of the National Research Council is planning a study on the professional master's degree. The Society for Industrial and Applied Mathematics is planning a study on increasing the usefulness of mathematical sciences master's-degree and PhD graduates in industry. The graduates of a professional master's degree program are ideally suited to applying existing techniques with a high level of understanding.

As indicated in the report *Educating Mathematical Scientists: Doctoral Study and the Postdoctoral Experience in the United States* (NRC, 1992b), some doctoral and postdoctoral programs in the mathematical sciences provide students with academic experience and professional development relevant to applied needs, including those of industry. These approaches need to be adopted more widely. Much of the new research in applied mathematics, statistics, operations research, and scientific computing has ties with industry. An increasing number of mathematical sciences researchers and students possess or are being taught the broad knowledge, communication skills, and team-building skills needed to address real-world problems. As a consequence, an increasing number of mathematical sciences PhDs are finding employment in industry (McClure, 1992).

The education of technical personnel of all branches of science and engineering must include increased exposure to the mathematical and computational sciences. Mathematical modeling and associated computations are becoming critical tools in the engineering design process. Scientists rely increasingly on computational methods and must have sufficient experience in mathematical/computational methods to be able to choose the correct methods and interpret the accuracy and reliability of the results. The mathematical education of engineers and scientists needs to change to reflect this new reality.

Much work is available for those interested in applying existing computational techniques to existing problems. Work is also available for those interested in developing new mathematical techniques to handle currently intractable problems. The Joint Policy Board on Mathematics is currently carrying out a study of possible changes in the performance measures (reward structure) in the academic community in order to encourage more direct contact of the mathematical sciences with other areas of endeavor, including industry.

As the science base and quantitative aspects of manufacturing grow and the reliance on subjective judgment and trial-and-error decrease, managers need stronger technical background in addition to humanistic skills. A product line's success in the marketplace is increasingly tied to anticipating and rapidly incorporating new technologies as well as keeping costs low through efficient, flexible production. An increase in mathematical and computational skills on the part of managers and professionals employed in non-technical positions would enhance the effectiveness of computer-based management tools. Managers should take an increasing number of courses in the mathematical sciences and computation as part of their curriculum in their chosen area.

C. IN-SERVICE TRAINING

Continual learning is becoming increasingly important for production workers, managers, and technical personnel. Life-long learning should be the norm for all. It should involve the acquisition of new technical skills and of original problem-solving approaches.

Some companies are now discovering that the quantitative skills required for performance of many old and new jobs are increasing faster than even an extensive in-service training program can help people to achieve. As of 1988, employers were already spending $25 billion annually on remedial education (MSEB, 1989, p. 4). In spite of the fact that the amount being spent by employers on remedial education is increasing rapidly, it is still not always possible to catch up with the mathematical requirements of increasingly technical jobs. Consider the experience of one manufacturing company that instituted a basic mathematical skills education program and a testing program a few years ago. The company had great success at first. However, the results soon deteriorated radically and it seemed that the more effort they put into the program, the worse the participants performed. Puzzled at this counterintuitive result, the company investigated. It turned out that the company, for utilitarian and legal (equal employment opportunity) reasons, had replaced the standardized tests that had been used when the program was initiated by tests based on internal studies that determined the real mathematical, statistical, and computational needs of each job. Not merely did the real needs of many jobs exceed the level of the standardized tests but the requirements for a number of those jobs had gradually moved upward. In addition, over the several years of the program, new jobs had replaced some old jobs and the requirements for the new jobs were significantly higher. The mathematical, statistical, and computational needs of the whole company had moved upward at a rate exceeding the ability of even a robustly pursued in-service training program to catch up.

Continuing education is needed not only for workers on the production floor, but also for low- and middle-level managers, technical personnel, and mathematical scientists working in or for industry. Broader background and communication skills should be the focus of this learning process for mathematical scientists and technical personnel. Managers should seek to keep or develop mathematical/computational skills that will allow them to understand and utilize technological achievements more effectively.

Chapter 6

The Path to the Future

The manufacturing of the future requires the creation and implementation of new technologies and a new management style. It requires a quantitatively educated workforce and management capable of taking the broad "system" point of view. Here we elaborate on a path that accomplishes the recommendations of Chapter 1.

A. TECHNOLOGY CREATION AND IMPLEMENTATION

Technologies for manufacturing can be divided into two types:

(a) generic, precompetitive technologies

(b) proprietary technologies

Precompetitive technologies are procedures in the engineering and scientific communities, well established or recently discovered, that are available to all, for example, through publication in scientific journals. A technology base of generic, precompetitive research is important for the success of both large and small industrial organizations. Technology, just like transportation, utilities, and an educated labor force, is a part of the infrastructure required by manufacturing industry. This infrastructure resides in the minds of the researchers in our universities and government laboratories. It is a fixed asset with the potential to attract and/or retain mobile global industries.

Proprietary research and technology are often based on precompetitive knowledge but contain additional novel ideas and data tailored to specific requirements for the manufacture of new products. At the present time of open markets and increasingly competitive industries, even proprietary knowledge tends to disseminate and thus to become part of the public domain. The ongoing vitality of our economy requires continuing renewal of both precompetitive knowledge and proprietary technology.

Industry employs two approaches to supplement its traditional proprietary R&D laboratories. One approach is to form consortia to develop proprietary technology. Costs and risks are shared among the groups that ultimately benefit from the technology. However, consortia are far from being a panacea for the technology development needs of industry. Smaller and newly emerging companies do not have the necessary resources or critical mass of scientists to participate in consortia. These small companies constitute one of the most dynamic sectors of the economy. Their success depends in part on having access to modern science and technology. A second approach is to recognize the public nature of precompetitive knowledge and to treat it as infrastructure. In this mode, industries are consumers of research and require conveniently available, state of the art access to this body of knowledge.

Technology implementation remains a weak link in the U.S. science-technology picture. Extensive precompetitive scientific and technical knowledge has accumulated in recent years. It is growing at an ever-increasing pace. However, industrial scientists and engineers, constrained by manufacturing schedules, often do not have the time and resources to avail themselves of this knowledge. Academic scientists can assist by taking the first steps in tailoring scientific knowledge to the specific requirements of industry.

Technology transfer within an industry (between design and manufacturing, for example) is even more critical a problem than that among academic, government, and industrial science. The requirements of a globally competitive economy driven by short design cycles, concurrent engineering, and shorter product runs call for a dramatic increase in technology transfer and cooperation between long-range research and development programs focused on specific products.

Increased world competition requires halving the time elapsed from concept to marketable product. For high-value-added research and technology to contribute in this climate, the passage of new ideas from the precompetitive to the proprietary stage must be accelerated. In order to improve technology utilization in manufacturing, a dramatic increase is needed in the level of cooperation among the academic, governmental and industrial sectors.

Successful large-scale government investments in science and technology have occurred in the areas of defense, medicine, and agriculture. In these cases, the investment ranged from basic science to applied technology and has produced U.S. strength and leadership in the associated technologies. We believe investment in industrial and manufacturing technologies and science will succeed as well. Here the mathematical sciences are part of a larger picture. Because of the central role assumed by computer simulation, the importance of computational science has increased. Cooperation among the mathematical and computational sciences, the other sciences, and engineering is essential to achieving world-class manufacturing technologies. Government laboratories have a large role to play in increasing this cooperation. In many cases, initial steps are already being taken in this direction.

In order to make the manufacturing processes more effective, we need to develop and continually renew our manufacturing technology infrastructure, that is, the generic research of the type discussed in this report. We need to develop this body of work and knowledge on a broad geographical base so that the industrial user can benefit from face to face contact with his/her regional university researchers. Regional universities should be encouraged to develop research areas that have impact on their regional industries. The academic mathematical sciences community must take a leading role in stimulating cooperation for technology implementation. One-on-one contact between individual researchers for the sharing, creation, and transfer of technology is required. Small groups geared toward specific coherent projects are a possible format to foster both the creation of generic technology and its transfer to manufacturing processes.

B. DEVELOPMENT AND SUPPORT OF MANAGEMENT PRACTICES

As mentioned in Ch. 4, the new model in manufacturing is based on decentralization on the one hand and on integration and interdependent planning on the other. This scenario will reduce middle-level management and will impose increased demands on higher-level management. Managers, in addition to retaining their traditional personal approach, will have to make many decisions based on quantitative information, sometimes from different types of databases.

The mathematical and computational sciences have an important role to play here in assisting management to develop strategies. The ability to access, process, and combine information from multiple databases is of great importance in decision making. Statistical methods will have to be incorporated into management practices on all levels. It is important that managers have sufficient technical background to understand and make use of all available information. When the model is only partially correct or the information is incomplete, limitations on the conclusions must be understood.

While government has a role in creating and renewing the humanistic and quantitative infrastructure for world-class management, more effective use of mathematical and computational methods in management practices should be achieved by a two-way cooperation of industry and academia. The performance measures for mathematical and computational scientists in academia should be adjusted to encourage cooperation with management specialists and economic and social scientists with the goal of contributing to the development and support of new management practices. The performance measures for managers should encourage testing and implementing new management practices.

C. EDUCATION AND TRAINING

An educated workforce is a basic economic asset for our country. Unfortunately, recent comparisons show poor performance across much of the K-12 educational system of the U.S. in comparison both to advanced and to rapidly developing nations. This deficiency is primarily due not to a decline in our historical standards but rather to a failure to match the advances of others. For example, vocational high schools in Tokyo now include calculus in their required curriculum. Societal values in the U.S. contribute to the problem. When not watching television, participating in sports, or socializing, most high school students prefer to work at part-time jobs rather than do homework.

The causes and possible cures of these problems are outside the scope of this report. They have been studied elsewhere (NRC, 1989a, 1990, 1991e) (NCTM, 1989). Here we will only say that these issues, including K-12 mathematics education, are a major responsibility of the mathematical sciences community. The pre-service and in-service training of teachers to prepare them to implement this blueprint remains a daunting task for mathematicians in higher education. The educational skills of the general populace are of great importance in manufacturing. Ultimately, our level of manufacturing will be limited by our general educational level.

"Uneducated" (below high school graduate plus specialized training) will be highly correlated with "unemployed" and "unemployable." With the downsizing of the workforce in many U.S. industries in the latest recession and the decline or stagnation in the standard for living for most Americans, this message is beginning to gain acceptance among students and parents. The NCTM Standards do an excellent job of addressing general mathematical literacy, but do not go the next step of teaching the mathematics for Taguchi methods and others types of quality control. Community colleges, which focus on career-oriented training, have been the fastest growing area of U.S. higher education and their mathematics enrollments have been growing much faster than enrollments at 4-year colleges and universities (CBMS, 1992). But their mathematics courses have not changed. New courses in mathematics for manufacturing need to be and can be developed for high schools and two- and four-year colleges.

While U.S. universities are among the global leaders in research and attract students from the entire world to graduate studies, there is much room for improvement in our undergraduate education. The training of future K-12 teachers of the mathematical sciences must be improved. There is also a need to continue to broaden the horizons of graduate education to prepare professional master's and doctoral graduates in the mathematical sciences for careers in industrial research and development (Chung, 1991).

Some action is already being taken in these areas by government, universities, and private foundations. The Alfred P. Sloan Foundation, for example, is developing a program of education for manufacturing that includes all levels from high school to PhD. A skillful teacher from one community college supported by this program imparted knowledge of statistical process control to workers in a food-processing plant. Not much formal mathematics was taught but the key notion of measuring variation was successfully transmitted. In an effort to provide a new generation of managers and manufacturing professors with a more integrated view of manufacturing, the Sloan Foundation is supporting master's and PhD programs in manufacturing that incorporate strong quantitative aspects of both technical and managerial knowledge.

D. THE KEY TO ACTION

The technology infrastructure for manufacturing in the United States has been created by the combined efforts of industry, government, and the research community. This infrastructure must be continually renewed and expanded. Changing the mathematical sciences so that they respond better to the applied needs of our technological society is a task that will require the cooperative efforts of faculty, departments, professional societies, industry and federal agencies. Changing manufacturing so that it can more rapidly incorporate progress in relevant technologies into better products will also require cooperative efforts of all concerned.

Simulation and computer-integrated design allow concurrent engineering and a shortening of the product design cycle while avoiding costly trial and error experimentation. Optimization of the design over a much larger set of alternatives becomes feasible using these methods. Improved sensors and pattern recognition allow manufacturers to tighten tolerances. Intelligent controls allow previously unattainable optimization of performance. Enterprise management is optimized through simulation of work station layout of production. Management structures are flatter. Decisions are more flexible and responsive to the special requirements of individual customers.

The areas emphasized in Chs. 3 and 4 are emerging areas of great importance in which the mathematical sciences, along with other branches of science and technology, have much to contribute. However, we should not lose sight of the huge number of more common areas of manufacturing, some of which were mentioned in Ch. 2, to which the mathematical sciences also contribute. To give but one example, in long conveyor belts used for strip mining, systematic oscillations in the nature of shock waves develop. Lack of investment by American companies in mathematical modeling and simulation to develop methods for avoiding or controlling these destructive waves resulted in complete loss of this area of manufacturing to Japanese and German firms, which invested in such research and improved product capability far beyond what was feasible in American factories.

Unfortunately, this is an all too typical and familiar story. One more industry "on the ropes" because of a failure to invest in technology. The particular mathematical technology needed to retain this area of manufacturing is not a focus of an emerging area but its absence will have a negative impact on the lives of many workers. The attention that we give to emerging areas such as those mentioned in Chs. 3 and 4 should not supplant attention to areas that are less dramatic but are equally important.

Our central message is that a revolution transforming design and manufacturing is taking place. This revolution includes contributions from many areas of the natural and social sciences and management practice. It requires the use of computers and utilizes mathematical modeling as one of its prime sources of ideas. The vast increase in computing power over the recent past has made useful to engineers and managers mathematics that once seemed impractical. Thirty years ago, inversion of small matrices for engineering calculations and resource planning by the simplex method were laborious. Today, procedures for inversion of huge matrices and optimization of huge systems are routinely carried out as part of the computational underpinnings of our modern manufacturing system. In the future, representation of complex interactions and solutions of full coupled systems will allow computational modeling of larger units and of the entire enterprise. In our era of increasingly complex computing, research in the mathematical and computational sciences plays an important role in creating the new technologies and organizational structures of the world's leading manufacturing enterprises.

Bibliography

Alic, J.A., L.M. Branscomb, H. Brooks, A.B. Carter, and G.L. Epstein, 1992, *Beyond Spinoff: Military and Commercial Technologies in a Changing World*, Harvard Business School Press, Boston.

Andreou, S.A., 1990, "A Capital Budgeting Model for Product-Mix Flexibility," *J. Manufacturing and Operations Management*, **3**, 5–23.

Baldwin, C.Y., 1991, "How Capital Budgeting Deters Innovation—And What to Do about It," *Res. Tech. Management*, **34**, No. 6, 39–45.

Banker, R.D., S.M. Datar, S. Kekre, and T. Mukhophdhyay, 1990, "Cost of Product and Process Complexity," in *Measures for Manufacturing Excellence*, R. S. Kaplan (ed.), Harvard Business School Press, Boston, Massachusetts, 269–290.

Bien, A.-P., and F. Cheng, 1991, "A Blending Method for Parametrically Defined Geometric Objects", in *ACM Symp. on Solid Modeling Foundations and CAD/CAM Applic.*, Austin, Texas, 339–350.

Bloch, E., and K.P. Conrad, 1988, "Manufacturing Systems: Meeting the Competitive Challenge" in National Academy of Engineering (NAE), 1988, *Design and Analysis of Integrated Manufacturing Systems*, Compton, W.D. (ed.), National Academy Press, Washington, D.C., 7–11.

Box, G.E.L., 1969, *Evolutionary Operation: A Statistical Method for Process Improvement*, Wiley, New York.

Brunet, P., I. Navazo, and A. Vinacua, 1991, "Octree Detection of Closed Compartments," in *ACM Symp. on Solid Modeling Foundations and CAD/CAM Applic.*, Austin, Texas, 87–98.

Camp, R.C., 1989, *Benchmarking: The Search for Industry Best Practices that Lead to Superior Performance*, Quality Press, Milwaukee, Wisconsin.

Carnevale, A.P., L.J. Gainer, and A.S. Meltzer, 1988, *Workplace Basics: The Skills Employers Want*, American Society for Training and Development and US Department of Labor, Washington, DC.

Cavendish, J.C., M.L. Wenner, J. Burkardt, C.A. Hall, and W.C. Rheiboldt, 1988, "Punch Stretching of Sheet Metal and Differential Equations on Manifolds," *Inter. J. Numer. Methods in Engin.*, **25**, 264–282.

Chandra, J. (ed.), 1992, *Scientific Issues in Intelligent Manufacturing*, Army Research Office, Research Triangle Park, North Carolina.

Chin, D., S.Y. Oh, S.M. Hu, R.W. Dutton, and J.L. Moll, 1983, "Two-Dimensional Oxidation," *IEEE Trans. Electron Dev.*, **ED-30**, 744–749.

Chung, F.R.K., 1991, "Should You Prepare Differently for a Non-academic Career?" *Notices of the American Mathematical Society*, **38**, 560 ff.

Chung, F.R.K., to appear, "Reliable Software and Communication: An Overview," *IEEE Journal on Selected Areas in Communications*.

Chung, K., and O. Richmond, to appear, "Ideal Forming, Part I: Homogeneous Deformation with Minimum Plastic Work," *Int. J. Mech. Sci.*

Clarke, E.M., O. Grumberg, D.E. Long, 1992, "Model Checking and Abstraction," in *POPL Proceedings*.

Clarke, F.H., V.F. Dem'yanov, and F. Giannessi (eds.), 1989, *Nonsmooth Optimization and Related Topics*, Proceedings of 4th Course of International School of Mathematics, Erice, June 20–July 1, 1988, Ettore Majorana Internat. Sci. Ser., Phys. Sci., **43**, Plenum, New York-London.

Conference Board of the Mathematical Sciences (CBMS), 1992, *Statistical Abstract of Undergraduate Programs in the Mathematical Sciences and Computer Science in the United States: 1990–91 CBMS Survey*, Mathematical Association of America, Notes and Reports, No. 23, Washington, D.C.

Crowder, S.V., 1986, *Kalman Filtering and Statistical Process Control*, Ph.D. Dissertation, Iowa State University.

Dautidis, P., and C. Kravaris, 1989, "Synthesis of Feedforward/State Feedback Controllers for Nonlinear Processes," *AIChE J.*, **35**, 1602–1616.

Dertouzos, M.L., R.K. Lester, R.M. Solow, and the MIT Commission on Industrial Productivity, 1989, *Made in America: Regaining the Productive Edge*, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Devenpeck, M.L., and O. Richmond, 1965, "Strip Drawing Experiments with Sigmoidal Die Profile," *J. Eng. Industry, Trans. ASME*, **87**, 425–428.

DeVore, R., B. Jawerth, and B. Lucier, 1992, "Image Compression through Wavelet Transform Coding," *IEEE Trans. Inform. Proc.*, **38**, 719–746.

Dixon, J.R., A.J. Nanni, and T.E. Vollmann, 1990, *The New Performance Challenge: Measuring Operations for World-Class Competition*, Dow Jones-Irwin, Homewood, Illinois.

Drexler, K.E., 1992, *Nanosystems: Molecular Machinery, Manufacturing, and Computation*, Wiley-Interscience, New York.

Educational Testing Service (ETS), 1989a, *From High School to College*, ETS Policy Notes, March 1989, Princeton, New Jersey.

Educational Testing Service (ETS), 1989b, *Gender Gap in Education*, ETS Policy Notes, October 1989, Princeton, New Jersey.

Faltermayer, E., 1990, "Is 'Made in the U.S.A.' Fading Away?," *Fortune*, **122**, No. 7, September 24, 1990, 62–73.

Faltin, F.W., G.J. Hahn, and W.T. Tucker, to appear, "Algorithmic Statistical Process Control: Some Practical Observations," *Internat. Statistics Review*, January 1993.

Foster, G., and M. Gupta, 1990, "Activity Accounting: An Electronics Industry Implementation," in *Measures for Manufacturing Excellence*, R.

S. Kaplan (ed.), Harvard Business School Press, Boston, Massachusetts, 225–268.

Friedman, A., 1988–1992, *Mathematics in Industrial Problems*, IMA Series in Mathematics and its Applications, Springer Verlag, New York, five volumes.

Friedman. L., 1989, "Mathematics and the Gender Gap: A Meta-Analysis of Recent Studies on Sex Differences in Mathematical Tasks," *Review of Educational Research*, **59**, 185–213.

Geman, S., and D. Geman, 1984, "Stochastic Relaxation, Gibbs Distributions, and Bayesian Restoration of Images," *IEEE Trans. Pattern Anal. Mach. Intell.*, **PAMI-6**, 721–741.

Gerber, P.D., 1988, "Exact Solution of the Proximity Effect Equation of a Splitting Method," *J. Vacuum Sci. Tech. B*, **6**, 432–435.

Goor, R.M., 1985, "A New Approach to Minimize Time Robot Control" in *Robotics and Manufacturing Automation*, M. Donath and M. Leu (eds.), American Society of Mechanical Engineering, Production Engineering Division, **15**, New York, 1–11.

Gunn, T., 1992, *21st Century Manufacturing*, HarperBusiness, New York.

Heim, J.A., and W. D. Compton (eds.), 1992, *Manufacturing Systems: Foundations of World-Class Practice*, National Academy Press, Washington, D.C.

Hoffmann, C.M., and R. Juan, 1992, *EREP: An Editable High-Level Representation for Geometric Design and Analysis*, Technical Report CSD-TR-92-055, Purdue University, West Lafayette, Indiana.

Hudson Institute, 1987, *Workforce 2000: Work and Workers for the Twenty-First Century*, William Johnston and Arnold Packer (eds.), Indianapolis, Indiana.

Inan, K.M., and Varaiya, P.P., 1989, "Algebras of Discrete Event Models," *Proc. IEEE*, **77**, 24–38.

Kaplan, R.S., 1989, "Management Accounting for Advanced Technological Environments," *Science*, **245**, 819–823.

Kaplan, R.S., 1990, "Limitations of Cost Accounting in Advanced Manufacturing Environments," in *Measures for Manufacturing Excellence*, R. S. Kaplan (ed.), Harvard Business School Press, Boston, Massachusetts, 15–38.

Kaplan, R.S., 1991, "New Systems for Measurement and Control," *The Engineering Economist*, **36**, 201–218.

Kaplan, R.S. and D.P. Norton, 1992, "The Balanced Scorecard—Measures that Drive Performance," *Harvard Business Review*, January–February 1992, 71–79.

Kuiken, H.K., 1990, "Mathematical Modelling of Etching Processes," in *Free Boundary Problems: Theory and Applications*, Vol. I, K.H. Hoffmann and J. Sprekels (eds.), Pittman Research Notes in Mathematics, **186**, Longman, Harlow, Essex, United Kingdom, 89–109.

Levine, J., and P. Rouchon, 1991, "Quality Control of Binary Distillation Columns via Nonlinear Aggregated Models," *Automatica*, **27**, 463–480.

Lin, J.-T., S.M. Meerkov, and F. Top, 1990, "Homogeneous Asymptotically Reliable Serial Production Lines: Theory and a Case Study," *IEEE Trans. Autom. Control*, **35**, 524–534.

Mathematical Association of America, 1992, *Heeding the Call for Change*, Lynn Steen (ed.), Washington, D.C.

Mathematical Sciences Education Board (MSEB), 1989, *Mathematics Education: Wellspring of U.S. Industrial Strength*, National Research Council, Washington, D.C.

McClure, D.E., 1992, "1991 Annual AMS-MAA Survey (Second Report)" in *Notices of the American Mathematical Society*, **39**, 573–581.

Morton, S., 1991, *The Corporation of the 1990's: Information Technology and Organizational Transformation*, Oxford University Press, Oxford.

Mumford, D., and J. Shah, 1989, "Optimal Approximations of Piecewise Smooth Functions and Associated Variational Problems," *Comm. Pure Appl. Math.*, **42**, 576–685.

Myers, R.H., 1971, *Response Surface Methodology*, Allynn and Bacon, Boston.

Myers, S., 1989, "The New Look at Capital Spending," *Fortune*, March 13, 1989, 115–120.

Nair, V.N. (ed.), 1992, "Taguchi's Parameter Design: A Panel Discussion," *Technometrics*, **34**, 127-161.

National Council of Teachers of Mathematics (NCTM), 1989, *Curriculum and Evaluation Standards for School Mathematics*, National Council of Teachers of Mathematics, Reston, Virginia.

National Critical Technologies Panel, 1991, *Report of the National Critical Technologies Panel*, National Critical Technologies Panel, Arlington, Virginia.

National Research Council (NRC), 1989a, *Everybody Counts: A Report to the Nation on the Future of Mathematics Education*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1989b, *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1990, *A Challenge of Numbers: People in the Mathematical Sciences*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1991a, *Applications of the Mathematical Sciences to Materials Science*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1991b, *The Competitive Edge: Research Priorities for U.S. Manufacturing*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1991c, *Mathematical Foundations of High-Performance Computing and Communications*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1991d, *Mathematical Sciences, Technology, and Economic Competitiveness*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1991e, *Moving beyond Myths: Revitalizing Undergraduate Mathematics*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1992a, *Combining Information: Statistical Issues and Opportunities for Research*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1992b, *Educating Mathematical Scientists: Doctoral Study and the Postdoctoral Experience in the United States*, National Academy Press, Washington, D.C.

National Research Council (NRC), 1992c, *Mathematical Opportunities in Nonlinear Optics*, National Academy Press, Washington, D.C.

National Research Council (NRC), to appear, Report of the Committee on the Mathematical Sciences in Genome and Protein Structure Research, National Academy Press, Washington, D.C.

Noppen, R., 1991, "Quality First: The Product at Porsche" in *Proceedings International Conference on the Application of Manufacturing Technologies*, Society of Manufacturing Engineers, Washington, D.C.

Oh, S.H., and J.C. Cavendish, 1982, "Transients of Monolithic Catalytic Converters: Response to Step Changes in Feedstream Temperature as Related to Controlling Automobile Emissions," *Ind. Eng. Chem. Prod. Res. Dev.*, **21**, 29–37.

Osher, S., and L. I. Rudin, 1990, "Feature-Oriented Image Enhancement Using Shock Filters," *SIAM J. Numer. Anal.*, **27**, 919–940.

Phillips, F.Y., and L. Spindler, 1991, "Product Life Cycle Planning and Global Location Dynamics" in *Concurrent Life Cycle Management*, F.

Y. Phillips (ed.), IC^2 Institute, The University of Texas at Austin, 199–210.

Rangogni, R., A.T. Uliana, G. Pini, and M. Patti, 1992, "Salt Intrusion Study into an Italian Aquifer" in *Computational Methods in Water Resources IX*, Vol. 2, T.E. Russell et al. (eds.), Elsevier Applied Science, London-New York, 359–366.

Sakurai, M., 1990, "The Influence of Factory Automation on Management Accounting Practices: A Study of Japanese Companies," in *Measures for Manufacturing Excellence*, R. S. Kaplan (ed.), Harvard Business School Press, Boston, Massachusetts, 39–62.

Schwartz, D.G., and G.J. Klir, 1992, "Fuzzy Logic Flowers in Japan," *IEEE Spectrum*, **29**, No. 7, 32–35.

Seifert, L.C., 1988, "Design and Analysis of Integrated Electronics Manufacturing Systems," in National Academy of Engineering (NAE), 1988, *Design and Analysis of Integrated Manufacturing Systems*, Compton, W.D. (ed.), National Academy Press, Washington, D.C.

Sethi, A.K., and S.P. Sethi, 1990, "Flexibility in Manufacturing: A survey," *Intern. J. Flexible Manufacturing Systems*, **2**, 289–328.

Shoham, Y., and M. Tennenholtz, 1992, "On the Synthesis of Useful Social Laws for Artificial Agent Societies (Preliminary Report)" in *Proceedings AAAI-92*, July 1992.

Society for Industrial and Applied Mathematics (SIAM), 1988, *Future Directions in Control Theory: A Mathematical Perspective*, SIAM, Philadelphia.

Solberg, J.J., 1988, "Integrated Manufacturing Systems: An Overview" in National Academy of Engineering (NAE), 1988, *Design and Analysis of Integrated Manufacturing Systems*, Compton, W.D. (ed.), National Academy Press, Washington, D.C., 1–6.

Soroush, M., and C. Kravaris, 1992, "Nonlinear Control of a Batch Polymerization Reactor: An Experimental Study," *AICHE*, **38**, 1429–1448.

Spanos, C.J., to appear, "Statistical Process Control in Semiconductor Manufacturing," *Proc. IEEE.*

Srivastava, R.K., 1991, "Valuation of Market Growth Opportunities" in *Concurrent Life Cycle Management*, F. Y. Phillips (ed.), IC^2 Institute, The University of Texas at Austin, 115–130.

Sussmann, H.J., 1983, "Lie Brackets, Real Analyticity, and Geometric Control" in *Differential Geometric Control Theory* (R.W. Brockett, R.S. Millman, and H.J. Sussmann, eds.), Birkhäuser, Boston.

Technology Administration, 1990, *Emerging Technologies: A Survey of Technical and Economic Opportunities*, U.S. Department of Commerce, Washington, D.C.

Vander Wiel S.V., W.T. Tucker, F.W. Faltin, and N. Doganaksoy, 1992, "Algorithmic Statistical Process Control: Concepts and an Application," *Technometrics*, **34**, 286–297.

Varaiya, P., and A. Kurzhanski (eds.), 1988, *Discrete Event Systems: Models and Applications, Lecture Notes in Control and Information*, **103**, Springer, New York.

Voelcker, H.B., 1988, "Modeling in the Design Process" in *Design and Analysis of Integrated Manufacturing Systems*, National Academy of Engineering (NAE), W.D. Compton (ed.), National Academy Press, Washington, D.C., 167–199.

Wang, F.E., 1985, *The Thermobile Nitinol Engine*, Report 851495, Society of Automotive Engineers, Warrendale, Pennsylvania.

Weiss, A., 1986, "A New Technique for Analyzing Large Traffic Systems," *Advances in Applied Probability*, **18**, 506–532.

Welch, W.J., and J. Sacks, 1991, "A System for Quality Improvements via Computer Experiments," *Comm. Statist. Theory Meth.*, **20**, 477–495.

Willemsen, M.F.C., A.E.T. Kuipev, A.H. Reader, R. Hokke, and J.C. Barbour, 1988, "*In Situ* Investigation of TiN Formation on top of $TiSi_2$," *J. Vacuum Sci. Tech. B*, **6**, 53–61.

Yano, C.A., and R. Rachamadergo, 1991, "Sequencing to Minimize Work Overload in Assembly Lines with Product Option," *Management Science*, **37**, 572–586.

Appendix A

Recent Studies of Emerging Technologies and Management Practices

In spring 1990, the Technology Administration of the U.S. Department of Commerce published *Emerging Technologies: A Survey of Technical and Economic Opportunities* (Technology Administration, 1990). This report identified the following twelve emerging technologies with annual sales projected to be $350 billion by the end of the century: advanced materials, supercomputers, advanced semiconductor devices, digital imaging technology, high-density data storage, high-performance computing, optoelectronics, artificial intelligence, flexible computer-integrated manufacturing, sensor technology, biotechnology, medical devices and diagnostics. This Department of Commerce report states that in 1990 the United States was judged to be ahead in 6 of the 12 technologies in comparison with Japan and in 9 of the 12 technologies in comparison with Europe. The United States was behind in 5 areas compared with Japan and 1 compared with Europe. Future trends are, however, less promising. In comparison with Japan, the United States is gaining ground in none of these areas: it is holding even in 2, and losing ground in 10. In comparison with Europe, the United States is gaining in 3 sectors, holding even in 6, and losing in 3.

In March 1991, the National Critical Technologies Panel (1101 Wilson Boulevard, Suite 1500, Arlington, Virginia, 22209), a panel appointed by the Director of the Office of Science and Technology Policy, published the *Report of the National Critical Technologies Panel* (National Critical Technologies Panel, 1991). This report identified 22 technologies critical to national economic prosperity and national security. Four of these twenty-two technologies concern manufacturing: flexible computer-integrated manufacturing, intelligent processing equipment, micro- and nanofabrication, and systems management technologies.

The report *Materials Science and Engineering for the 1990s: Maintaining Competitiveness in the Age of Materials* (NRC, 1989b) discusses research in materials science, which the U.S. needs to remain technologically competitive in the international arena. Scientific and technological frontiers of the field are explored both from the point of view of materials classes and from the point of view of the four elements of the field of materials science: synthesis and processing, structure and composition, properties, and performance. The book discusses the role that industry, the federal government, and universities should play in conducting future research. The book concludes with an appraisal of the national strategies of the international competitors in the field of materials science and engineering.

The book *21st Century Manufacturing* (Gunn, 1992) discusses from a management perspective the steps needed to become a world-class manufacturer. Taguchi methods of statistical quality improvement, information technology, inventory management and computer-integrated product and process design are among the technical issues emphasized.

The report *The Competitive Edge: Research Priorities for U.S. Manufacturing* (NRC, 1991b) is the product of a study conducted by the Manufacturing Studies Board of the National Research Council. It identifies and analyzes research needs in five critical areas of manufacturing: intelligent manufacturing control, equipment reliability and maintenance, advanced engineered materials, manufacturing skills improvement, and the product realization process.

In *Manufacturing Systems: Foundations of World-Class Practice* (Heim and Compton, 1992), the National Academy of Engineering identifies ways to make the system of manufacturing efficient, responsive, and effective. The report argues that the modern manufacturing organization cannot be competitive if it continues to operate as a loosely connected group of independent elements.

The book *Beyond Spinoff: Military and Commercial Technologies in a Changing World* (Alic et al., 1992) describes the changes associated with a global economy and the end of the Cold War.

Appendix B

Areas of the Mathematical and Computational Sciences in Manufacturing

Many mathematical and computational methods, including those of differential equations, probabilistic models, statistics, combinatorial analysis and numerical analysis have been seen in Chs. 2–4 to be important not merely in one area of manufacturing but often simultaneously in many. For example, computational geometry is needed for automatically generating assembly plans, interpreting engineering drawings, and inspecting NC (numerically controlled) code for machine tools. It is also required for robot motion planning, analyzing structural properties, inspecting finished parts, and performing simulations of physical systems by "virtual reality." The tools and concepts for standard manufacturing technologies as well as for newly emerging technologies such as quantum level computational devices reside within a common framework of mathematical sciences activities. What is needed for manufacturing is first, the vitality of that core framework and second, extensions of it in directions important for a manufacturing research agenda.

The mathematical and computational research issues that arise in various areas of manufacturing include

- Homogenization, solid and fluid modeling
- Linear and nonlinear ordinary and partial differential equations
- Numerical analysis, finite element methods, adaptive methods, scientific computing, parallel computing
- Integral equations, inverse scattering, deconvolution
- Discrete equations

- Linear and nonlinear control problems for ordinary and partial differential equations, feedforward control, fuzzy logic (Control problems for partial differential equations can be approximated by control of an infinite system of ordinary differential equations. One refers to such systems as infinite-dimensional control systems or distributed parameter systems. *Future Directions in Control Theory: A Mathematical Perspective* (SIAM, 1988) is an excellent reference work.)

- Dynamical systems, fractals (dendritic growth), chaos

- Experimental design, Monte Carlo methods, high-dimensional regression analysis

- Stochastic models, Markov chains, queuing, simulation, discrete event simulation

- Operations research, optimization

- Pattern matching, variational problems and Bayesian methods in machine vision, shock capturing and shock tracking for edge enhancement

- Differential geometry, computational geometry, visualization, virtual reality, robotics, Lie algebras, topology, combinatorics

- Network theory, graph theory, neural nets

For additional information on the many ways in which the mathematical and computational sciences contribute to manufacturing, one can consult the report *Scientific Issues in Intelligent Manufacturing* (Chandra, 1992) and the five-volume series *Mathematics in Industrial Problems* (A. Friedman, 1988–1992). For further information on the contributions of the mathematical and computational sciences to the aircraft, semiconductor and computer, petroleum, automobile, and telecommunications industries, the report *Mathematical Sciences, Technology, and Economic Competitiveness* (NRC, 1991d) can be consulted. A matrix cross-indexing manufacturing and management technologies with distinct mathematical and computational technologies would be of great benefit to both the manufacturing community and the mathematical/computational sciences community. Such a matrix should be created and published in a future report.

Fisher's statistical procedures for experimental design, Shannon's seminal work on information theory, and von Neumann's pioneering work on computers are examples of ground-breaking mathematical discoveries originating in applications. Manufacturing is a fertile source of practical problems that can spark important contributions in the mathematical and computational sciences themselves.

THE MATHEMATICAL AND COMPUTATIONAL SCIENCES IN EMERGING MANUFACTURING TECHNOLOGIES AND MANAGEMENT PRACTICES

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ISBN 0-89871-307-2