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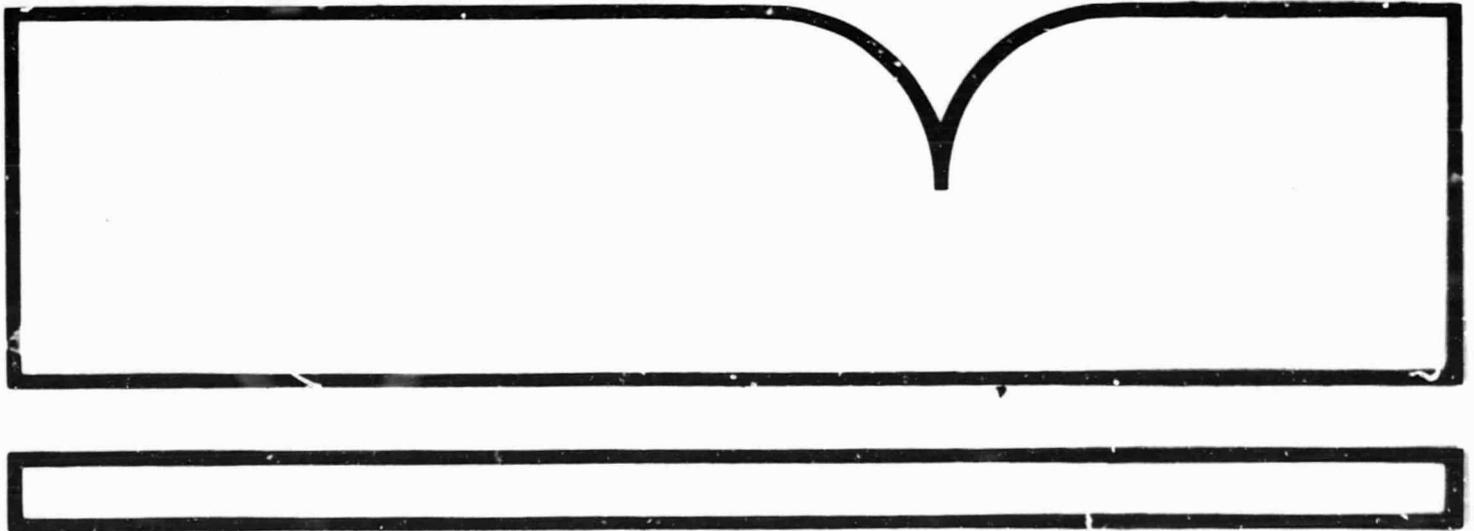
Computer Integration of Engineering
Design and Production
A National Opportunity

National Research Council, Washington, DC

Prepared for

National Aeronautics and Space Administration
Washington, DC

Oct 84



U.S. Department of Commerce
National Technical Information Service

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PB85-128429

Computer Integration of Engineering Design and Production

A National Opportunity

**Committee on the CAD/CAM Interface
Manufacturing Studies Board
Commission on Engineering and Technical Systems**

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SPRINGFIELD, VA 22161

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No. DA5 128429	
4. Title and Subtitle Computer Integration of Engineering Design and Production: A National Opportunity			5. Report Date Oct. 1984	
7. Author(s)			6.	
9. Performing Organization Name and Address National Research Council Commission on Engineering and Technical Systems 2101 Constitution Avenue, NW Washington, DC 20418			8. Performing Organization Rept. No.	
12. Sponsoring Organization Name and Address National Aeronautics and Space Administration			10. Project/Task/Work Unit No.	
15. Supplementary Notes			11. Contract(C) or Grant(G) No. (C) NASW-3811 (G)	
16. Abstract (Limit: 200 words) The National Aeronautics and Space Administration (NASA), as a purchaser of a variety of manufactured products, including complex space vehicles and systems, clearly has a stake in the advantages of computer-integrated manufacturing. Two major NASA objectives are to launch a Manned Space Station by 1992 with a budget of \$8 billion, and to be a leader in the development and application of productivity-enhancing technology. At the request of NASA, a National Research Council committee visited five companies that have been leaders in using CIM. Based on these case studies, the report describes technical, organizational, and financial issues that influence computer integration, offers guidelines for its implementation in industry, and recommends the use of CIM to manage the space station program.			13. Type of Report & Period Covered Final	
17. Document Analysis a. Descriptors computer-integrated manufacturing, CAD/CAM, data integration b. Identifiers/Open-Ended Terms NASA, space station, IGES, IPAD, ICAM, PDDI, AMRF c. COSATI Field/Group			14.	
18. Availability Statement distribution is unlimited		19. Security Class (This Report) Unclassified		21. No. of Pages 70
		20. Security Class (This Page) Unclassified		22. Price

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A NATIONAL OPPORTUNITY

Committee on the CAD/CAM Interface
Manufacturing Studies Board
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1984

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study was supported by Contract NASW-3811 between the National Aeronautics and Space Administration and the National Academy of Sciences.

A limited number of copies
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Manufacturing Studies Board
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2101 Constitution Avenue
Washington, D.C. 20418

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PREFACE

The National Aeronautics and Space Administration (NASA), as a purchaser of a variety of manufactured products, including complex space vehicles and systems, clearly has a stake in the advantages of computer-integrated manufacturing. Two major NASA objectives are to launch a Manned Space Station by 1992 with a budget of \$8 billion, and to be a leader in the development and application of productivity-enhancing technology.

NASA's major effort in integration has been the Integrated Program for Aerospace Vehicle Design (IPAD), directed at computer-aided design. To extend its work into the broader arena of computer-integrated manufacturing, NASA asked the National Research Council (NRC) to conduct an investigation using case studies as the basis for recommendations designed to:

- clarify the data management requirements in computer-integrated manufacturing, and
- correct deficiencies in current efforts that address the interaction between the engineering design of a product and its production.

The NRC, through its Manufacturing Studies Board, formed the Committee on the CAD/CAM Interface in September 1983 to respond to NASA's request. The Committee comprises 12 members from industry and academia with experience in research, design, production, computers, and management. The Committee met four times during a one-year period. In addition, it conducted five site visits to industry and met with the program staffs of the three major federal programs involved in computer-integrated manufacturing.

For case studies, the Committee selected five companies that have made significant progress toward integration. These leading companies hosted two-day site visits by three to five Committee members. The Committee developed a questionnaire (Appendix A) to solicit from the companies their definitions of integration and information on the planning process, execution of the integration plan, contents of the data base, effects of integration on the organization, and measures of progress. These case studies:

- identified the data flows and data management required for effective integration of computer-aided engineering design with computer-aided production, and
- evaluated significant problem areas or trends in integrating CAD and CAM.

The insights gained from the five companies, combined with the Committee members' own experience and information on federal programs, are the basis for the site visit report in Chapter 2 and the analysis of issues in Chapter 3. These, in turn, lead to the recommendations in Chapter 4 for specific actions by NASA, other federal agencies, and U.S. manufacturing companies.

The Committee on the CAD/CAM Interface is solely responsible for this report. A number of others, though, have made invaluable contributions. First of all, the report would not have been possible without the help of Deere and Company, General Motors Corporation, Ingersoll Milling Machine Company, McDonnell Aircraft Company, Westinghouse Defense and Electronics Center, the IPAD program staff at the Boeing Commercial Airplane Company, the Air Force Integrated Computer Aided Manufacturing program, and the National Bureau of Standards Automated Manufacturing Research Facility. At all these places, Committee members were welcomed by many people who gave generously of their time, insights, and knowledge. In addition, Samuel Venneri and Harry Sonnemann of NASA gave important guidance to the Committee's work.

Staff Officer Janice Greene was primarily responsible for the management of the study and participated in the analysis and writing. George Kuper, Executive Director of the Manufacturing Studies Board, contributed much to the substance and process of the Committee's discussions. Jozsef Hatvany of the Computer and Automation Institute, Hungarian Academy of Sciences, contributed Appendix C, on CAD/CAM outside the United States. Consultant Harold Davidson provided information on federal programs. Kenneth Reese edited this report. George Krumbhaar, Gerald Susman, and Margaret Dewar reviewed the draft and suggested improvements. Georgene Menk was responsible for the administrative work of the Committee, and Lucy Fusco and Donna Reifsnider provided administrative support and typed this report.

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EXECUTIVE SUMMARY

The most critical problem faced by too many U.S. industrial executives today is the steady decline in their companies' competitiveness at home and abroad, and the resultant loss in market share. A major reason for the decline has been the gradual emergence of a technology gap in manufacturing. It has not been a single identifiable event, but a slow erosion of the technological foundation of manufacturing. The keys to regaining competitiveness in most U.S. manufacturing industries are quality, productivity, and responsiveness in bringing new products to the marketplace. A primary technology for attaining these attributes, across industries, is computer-integrated manufacturing.

Manufacturing includes all activities from the perception of a need for a product, through the conception, design, and development of the product, production, marketing, and support of the product in use. Every action involved in these activities uses data, whether textual, graphic, or numeric. The computer, today's prime tool for manipulating and using data, offers the very real possibility of integrating the now often fragmented operations of manufacturing into a single, smoothly operating system. This approach is generally termed computer-integrated manufacturing (CIM).

Computer-integrated manufacturing can be employed at many levels short of total integration, which in fact has not yet been achieved anywhere. Manufacturers who are leaders in CIM typically have concentrated their efforts in two areas:

- computer-aided design (CAD), which applies the computer to the creation, modification, and evaluation of product design, and
- computer-aided manufacturing (CAM), which applies the computer to the planning, control, and operation of a production facility.

Manufacturers that concentrated on CAD and CAM in the early stages of the technology's application, however, generally paid little attention to the interface between the two. In most companies, the activities were in different departments with heterogeneous computers and languages, inconsistent objectives, and little or no consideration given to the transfer of information between the two in either

direction. Such programs, in consequence, have often been "islands of excellence" separated by poor communication, diverse goals, and adversarial relationships.

Recognizing that the CAD/CAM interface is a key barrier to computer-integrated manufacturing, the National Aeronautics and Space Administration (NASA) asked the National Research Council (NRC) to investigate the current status of industrial efforts to improve the interface. The NRC, through its Manufacturing Studies Board, formed the Committee on the CAD/CAM Interface to respond to the request.

NASA has two major objectives that the Committee's recommendations address. These are:

1. To launch a Manned Space Station by 1992 with a budget of \$8 billion.
2. To be "a leader in the development and application of advanced technology and management practices which contribute to significant increase in Agency and National productivity" (NASA Administrator's goal #8). Objective 4 under this goal is to "...conduct joint contractor-NASA pilot productivity incentive programs on a major development project and for a major support service activity." Objective 5 is to "establish a capability for agencywide sharing of CAD/CAM techniques by FY 1984."

Specifically, NASA asked that the Committee use case studies as a basis for recommendations designed to:

- clarify the data management requirements in computer-integrated manufacturing, and
- correct deficiencies in current efforts that address the integration between the engineering design of a product and its production.

In responding to the charge, the Committee visited five companies that have been leaders in implementing computer-integrated manufacturing and studied three major government programs in this field. It became clear that the problem is much broader than the CAD/CAM interface. Information is used in manufacturing from the conception of a product to its delivery and use in the field. Leaders in U.S. manufacturing have already realized substantial benefits from the computer, but the potential benefits of computer integration may be much greater. One of the best documented examples of the benefits of integrating information is Boeing's experience with its most recent airplane programs, the 757 and 767. The company realized significant improvements in design and production, reduction of part shortages, adherence to schedules, and budgetary performance in comparison with earlier airplane programs.

Other examples of excellence in design, reduced work in process, lead-time reduction, and improved productivity and quality were observed in all the firms interviewed by the Committee. In one, for example, the adoption of CIM led to a reduction in the time from release of the design to assembly from 18 weeks to 4 weeks, and

inventory was reduced from three months' supply to one month. These improvements were due in large part to integrated data handling, often manual, from start to finish of the manufacturing process. The values shown below are representative of the intermediate benefits of 10- to 20-year efforts. Further benefits are expected to accrue as full integration is approached.

Benefits Achieved

Reduction in engineering design cost	15-30%
Reduction in overall lead time	30-60%
Increased product quality as measured by yield of acceptable product	2-5 times previous level
Increased capability of engineers as measured by extent and depth of analysis in same or less time than previously	3-35 times
Increased productivity of production operations (complete assemblies)	40-70%
Increased productivity (operating time) of capital equipment	2-3 times
Reduction of work in process	30-60%
Reduction of personnel costs	5-20%

The challenge of manufacturing management is broadening from the historic interest in handling and processing materials to include the management of information that controls those processes. This major substantive shift is the result of marketplace pressures, which demand greater manufacturing flexibility, improved quality and performance, and faster delivery. Factory operations have always been driven by marketplace needs. Unlike the past, however, the market pressures that necessitate computer-integrated manufacturing are not directly related to the technology. The computer integration of factory data allows higher quality, shorter cycle time between design and production, efficient production of small batches, and faster incorporation of design changes--which in turn respond to the market demand for flexibility, quality, and delivery.

RECOMMENDATIONS

The recommendations that follow are based on the need to support progress in factory data management techniques and increase the use of CIM throughout the U.S. manufacturing base. One objective of these recommendations is to ensure access to the knowledge already gained by those manufacturers that have as much as 20 years of experience with the concept. A second and more significant objective arises from the recognition that implementation of CIM exceeds the capabilities of most individual manufacturing organizations. This fact implies the need to develop and disseminate knowledge of factory data management issues by more collective action than has occurred to date.

1. The Committee recommends that the National Aeronautics and Space Administration adopt a strategy of computer-integrated manufacturing for its Manned Space Station program.

The use of CIM for the Manned Space Station is essential to meeting the program's administrative goals--a manned station in space in 1992 at a total cost of \$8 billion--because manual coordination of the data to support the design and manufacturing of systems components would be time consuming and prone to error. Adoption of a clear CIM strategy by NASA would avoid the evolution of incompatible approaches as each manufacturer or supplier prepares to respond to NASA's space station requirements. Unless the efforts of the hundreds of companies supporting the space station program are coordinated by means of CIM, design engineering and production errors are likely to proliferate. Finding and correcting these errors would entail substantially higher costs, longer development time, and perhaps reduced operational capability.

A secondary reason for the use of CIM in the Manned Space Station program is to further the development and use of the technology. NASA has a legitimate role in sponsoring the development and diffusion of technology, such as CIM, that is important to the country but that initially, at least, is beyond the resources of a single company to deliver. The Apollo and Space Shuttle programs provide clear precedents for NASA-funded creation and diffusion of new technologies.

Adoption of a strategy of computer-integrated manufacturing would require implementation of CIM throughout the pertinent operations of both NASA and its contractors. Such an effort would involve many combinations of computer equipment from various vendors. To permit communication among these heterogeneous systems, NASA would have to adopt standards for data definition, data formats, languages, and protocols. The communications problem would be difficult but, in the Committee's opinion, surmountable. In solving it, NASA could draw on four existing federal efforts: the Integrated Program for Aerospace Vehicle Design (IPAD), funded by NASA and the Navy; the Air Force's Integrated Computer Aided Manufacturing (ICAM) program; the Product Definition Data Interface (PDDI) effort under ICAM; and the National Bureau of Standards' Automated Manufacturing Research Facility (AMRF).

2. The Committee recommends that companies form consortia to pursue research and other projects in CIM not readily undertaken by individual companies.

The technological accomplishments required to achieve CIM entail enormous expense, creativity, planning efforts, and amounts of time. Only the largest U.S. manufacturers, or those responding to a specific marketplace requirement for CIM, can be expected to apply the needed resources to their CIM efforts. Yet the Committee believes that a majority of U.S. manufacturers will not be able to remain competitive in the quality, timeliness of delivery, and cost of their products unless they use CIM. Therefore, cooperative efforts among companies will enable a broader base of U.S. industry to achieve CIM.

To speed the rate of application of existing knowledge about CIM, and to identify priorities for research, groupings of companies should organize to pool their efforts. Individual company applications of CIM technology will vary in hardware, software, and order of implementation. However, many issues in data communication, data bases, and process modeling surpass the abilities of single companies and could best be resolved cooperatively. The Department of Commerce's R&D Limited Partnership program may offer a useful mechanism for forming consortia.

3. The Committee recommends that the Computer and Automated Systems Association compile knowledge of CIM technology, drawing on both industrial and governmental sources, and make it available to industry, to universities, and to governmental agencies.

All of the companies involved in the Committee's site visits had spent a good deal of time planning and organizing for computer-integrated manufacturing. Companies that are not as far as these leaders in their thinking about CIM should not have to develop their plans from scratch. If existing information were available in an organized form from a central place, diffusion of CIM technology would accelerate. The intent of this recommendation is that existing information on CIM be collected, organized, and disseminated to current and prospective users. New information would be added as it became available.

The Computer and Automated Systems Association (CASA) of the Society of Manufacturing Engineers has the constituency, mandate, and authority to carry out this recommendation. CASA's membership comprises engineers with an interest in and experience in computer-integrated manufacturing.

4. The Committee recommends that the federal government continue to undertake research to resolve fundamental technical issues related to computer-integrated manufacturing.

Resolution of the technical issues in Chapter 3 requires more research than a single company can undertake on its own. Data communication in a heterogeneous system, validation and consistency of

data, representation of textual and geometrical data, expert systems, and analytical models of manufacturing processes are all risky areas of research, requiring multiyear, cooperative efforts. Solutions to these problems are needed to advance work in computer-integrated manufacturing.

We believe that the national research agenda should be revised to incorporate these needs and that the efforts initiated should be given long-term support. The Federal Coordinating Council for Science, Engineering, and Technology, chaired by the President's Science Adviser, might be the appropriate group to manage federally funded research related to CIM. Federal science policy-makers need sufficient understanding of the generic research issues outlined in this report so that a small percentage of the federal research budget can be effectively directed toward building the cumulative knowledge base necessary for progress on these issues.

5. The Committee recommends that federal agencies that purchase manufactured goods accept digital data sets compatible with the Initial Graphics Exchange Specification, rather than requiring conventional drawings, as a deliverable item under contracts.

This recommendation applies to all federal agencies that procure manufactured goods with high tolerance specifications and require the ability to replicate these products. These agencies include NASA, the Departments of Defense and Energy, and others.

Some federal contractors already handle graphical material internally in the form of digital data and create conventional drawings solely to satisfy federal contracts. Besides the inefficiency of this procedure, errors that creep into drawings produced only to satisfy contracts may not be found until another contractor tries to use the drawings. Acceptance of digital data by the government would obviate this problem and, more importantly, would promote the creation of computer links between organizations as well as within them.

The requirement for data in a form compatible with the Initial Graphics Exchange Specification is recommended because it is the only communications protocol as yet widely accepted in industry. It establishes an initial basis for direct digital exchange of graphical data and has been adopted as a standard by the American National Standards Institute.

6. The Committee recommends that manufacturing companies considering investment in product design or manufacturing process technology consider computer-integrated manufacturing.

Adoption of CIM technology is essential to the maintenance or recovery of competitiveness by U.S. manufacturers in domestic and world markets. Companies regularly find themselves losing ground to competitors who are introducing CIM. Nevertheless, far too few companies in this country are working seriously to adapt the concept to their operations.

Companies that are about to invest in product design or manufacturing process technology should be aware of the potential benefits of CIM, as well as the consequences of postponing the decision to plan and gradually implement an integrated system. Competition in manufacturing can only become more intensive, and companies that do not move into computer-integrated manufacturing, the Committee believes, face a dim future.

A ROLE FOR NASA

Concerted use of CIM technology in this country clearly can improve our industrial competitiveness. The companies that lead the nation in this technology all told the Committee that they have gained from investing in it and that companies that hope to compete successfully either domestically or overseas in the years ahead must invest in CIM. It is time for U.S. industry to push toward adoption of CIM, and NASA, through its Manned Space Station program, is in an ideal position to lead the transition. Even more important, it is in NASA's interest to use CIM to manage and coordinate the Manned Space Station program.

1 MANUFACTURING, COMPUTERS, AND INTEGRATION

Manufacturing is the conversion of raw materials into end products. It includes all activities from the perception of a need for a product, through the conception, design, and development of the product, production, marketing, and, ultimately, support of the product in use. All these activities are closely related and interactive and, therefore, are best treated as parts of a single system.¹

Every action in manufacturing uses data, whether textual, graphic, or numeric. These data are generated, transmitted, transformed, and used in every step from the perception of need to the design of a product that meets that need; in every step of the conversion of raw materials into finished products; and in every managerial action necessary to produce a product on time, within budget, and to specification.

The computer is the world's first machine for magnifying the power of the human mind. It has been used by business for generating, storing, transmitting, transforming, and using data. Within the past two decades the computer has increased the ability to store and manipulate data by orders of magnitude. Even more importantly, computing techniques now permit analyses and solution of problems never before possible.

COMPUTER-INTEGRATED MANUFACTURING

Starting with F.W. Taylor and scientific management,² near the turn of the century, companies have progressively divided manufacturing activities into their basic elements and developed specialized equipment and labor to handle them efficiently. The result has been large increases in output and quality, relative to cost. At the same time, this division has so fragmented the functions of manufacturing that beneficial interactions may have been lost. As a result of the fragmentation and the difficulty of visualizing the system as a whole, most efforts to increase the cost-effectiveness of manufacturing have been directed at optimizing its bits and pieces independently, resulting in far from optimal performance of the system.

Computers offer the possibility of reintegrating these fragmented functions into a single, smoothly operating, manufacturing system with reduced total manufacturing costs and turnaround times, and improved quality. Computer-integrated manufacturing (CIM) in a manufacturing enterprise occurs when:

- all the processing functions and related managerial functions are expressed in the form of data,
- these data are in a form that may be generated, transformed, used, moved, and stored by computer technology, and
- these data move freely between functions in the system throughout the life of the product,

with the objective that the enterprise as a whole have the information needed to operate at maximum effectiveness.

The computer has been used in manufacturing for years. Perhaps its most common early use was in controlling machine tools--first offline, via punched tapes, and then online, via direct numerical control (DNC). The computer has been used successfully in a variety of applications for communication of data among a limited number of manufacturing functions. A number of companies have focused their activities on two broad areas:

- computer-aided design (CAD), which applies the computer to the creation, modification, and evaluation of product design, and
- computer-aided manufacturing (CAM), which applies the computer to the planning, control, and operation of a production facility.

Of the countless interactions required in a fully integrated manufacturing system, the interface between engineering design and production--that is, between CAD and CAM--is currently a major stumbling block in achieving computer integration. In the movement of a product from initial concept to finished form, the organizational division between engineering design and production has been, until very recently, the most clear-cut and accepted. As a result, efforts to bridge this interface have lagged progress in the computer integration of applications within those areas.

The CAD/CAM interface, though presenting a great challenge to integration, should not be separated from other problems in developing a CIM system. Examining only the CAD/CAM interface could perpetuate the existing fragmentation. This report will emphasize the interface between engineering design and production, but within the context of the integration of a broader range of data and functions necessary to optimize a factory's operation.

THE CONSEQUENCES OF COMPUTER-INTEGRATED MANUFACTURING

The computer can provide manufacturing with two powerful, never-before-available capabilities:

- flexible, data-driven automation--for example, the choice of a DNC program as a function of the part to be processed
- online decision-making algorithms--the ability to determine system status, generate alternatives, and choose the best one, based on objective criteria

The computer has the potential to provide these capabilities not only for limited portions of manufacturing activity, but also for the entire manufacturing system. This use of the computer is producing what is being called the computer-integrated manufacturing system, portrayed generally in Figure 1.

In today's manufacturing environment in the United States, both managers and engineers often treat manufacturing as a unidirectional system in which data and information flow only downstream, from product design to production to shipping. Realization of the potential offered by CIM requires a data handling system that assures free access to data (though not necessarily to change data) and the flow of data among all parts of a manufacturing system. Included in this data flow is information on the customer's expectations as well as information on design and production of the product.

Information in a CIM system is extracted from fully automated segments of a process for use in controlling, planning, or modifying inputs into the process. Thus, a system having an objective and a means of detecting deviations from that objective can take corrective action to decrease the deviation. This technique is commonly called "feedback" control.

Information from segments that depend wholly or partially on human judgment is made completely available to the user, and computer facilities for simulation and prediction are available. This is neither "feed forward" nor "feed back," but concurrent perception of all factors entering a decision. Until this free flow of information is accepted, the CAD/CAM interface will remain a barrier.

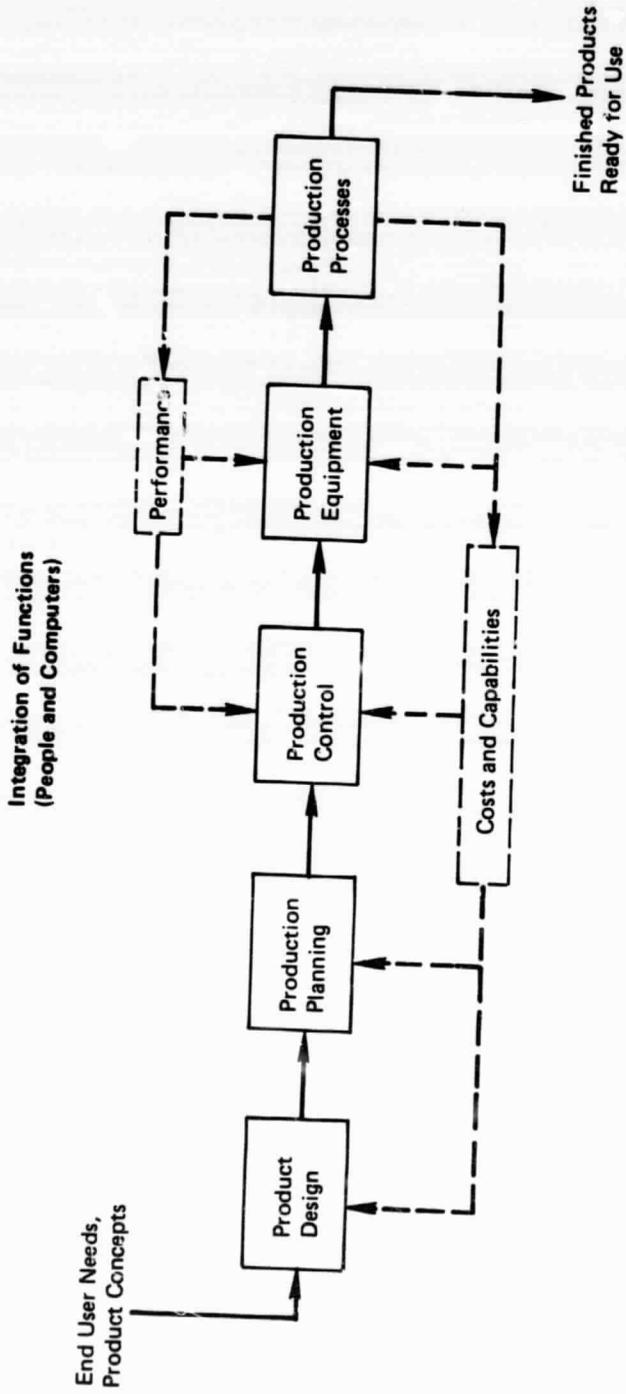
The path in Figure 1 labeled "cost and capabilities" is directed at improving cost-effectiveness by enabling both design and manufacturing engineers to evaluate the consequences of each alternative design concept and each decision on production methods. The "performance" path will incorporate quality control in the system.

A GLIMPSE AT THE INTEGRATED FACTORY OF THE FUTURE

Full CIM has not been realized in practice anywhere in the world, although many systems have major elements in operation. For instance, flexible manufacturing systems (FMS) have many of the characteristics of CIM applied to production. One FMS is described in Appendix B. From a projection of the operation of present systems, it is possible to envision what the factory of the future may be like.

A product will be designed using an iterative dialog between the design engineer and a computer. The designer will supply the design concepts and requirements and do the creative work. The computer will supply standard design elements and other stored, experience-based

Figure 1



information and perform the design calculations. During this design process, the computer will constantly retrieve and evaluate information on the manufacturing costs and capabilities of the equipment and processes required to produce each of the alternatives conceived by the designer. The computer will assist the engineer in achieving a design alternative that is the best compromise among product cost, quality, durability, and producibility.

Concurrently, production planning will use the same data to choose the proper equipment and processes, sequence of operations, and operating conditions for manufacturing the product. This numerical information in turn will be used to control the array of machines and equipment that will produce the parts and assemble the product. These machines and equipment will be capable of automatically adjusting the operating conditions, handling parts, selecting tooling, and carrying out a variety of fabrication processes and assembly. The machines will be self-regulating as a consequence of information provided to the control system through the path labeled "performance" in Figure 1.

This system will continually receive information about the actual performance of the equipment and processes and compare it with the "ideal" performance planned in the earlier phase. Should performance begin to depart from the plan, the system will override the original instructions, adjust the operating conditions of the machines and processes to compensate, and automatically reschedule as necessary.

The machines and equipment will have self-diagnostic and predictive capabilities. Should an impending malfunction be projected, they will take appropriate corrective action, including automatic replacement of defective modules in the system. Further, the machines will conduct automatic, in-process inspection of the product at each stage so that any impending deviations from the original specifications can be automatically corrected and the product held within prescribed tolerances. In a computer-integrated manufacturing system, quality means the prevention of problems, not detection and correction. Thus, every final assembled product will conform with the original design concepts and requirements. This ideal system will also incorporate data for updating product design.

GETTING TO CIM

It is difficult to justify new technology by traditional cost-benefit methods. The costs are current and easily measured, while the benefits are often realized in the future and not easily quantified. CIM, in particular, is very difficult to quantify because its benefits are dispersed through the entire organization, do not necessarily occur on a uniform, consistent basis, and frequently depend on the transformation of raw data into useful information. The value of the information added by CIM is highly dependent on the perspective of the individual.

In its attempt to document the benefits of CIM to firms that pioneered its use, the Committee found that much of that information was proprietary. Clearly, the firms that use CIM consider it a

competitive advantage. In at least one industry, computer manufacturers, CIM has become a competitive necessity. Many firms are using an integrated approach to design of their product and the process by which it is to be produced. The main tool for the integration of the various design processes is a central engineering data base. Proprietary systems are used to integrate all of the design processes from technology insertion, logic design (both logic and fault simulation), and physical design through to inputs to fabrication and assembly. The same data base is used throughout the hierarchy of the design process.

In the early 1980s, with the advent of electronic designer work stations, local area networks consisting of sets of microcomputers available to the design engineers were added to the in-house systems. Over the past several years, companies have integrated the data bases available on these local area network nodes with the central engineering data bases. Integration of these data bases saved both time and money by reducing the amount of rework required. In some cases, rework was virtually eliminated because of the elimination of human intervention in the various elements of product design.

NOTES

1. Joseph Harrington, Jr., Understanding the Manufacturing Process (New York and Basel: Marcel Dekker, 1984).
2. Frederick W. Taylor, The Principles of Scientific Management (New York and London: Harper and Brothers, 1911). See also, for example, Daniel Nelson, Frederick W. Taylor and the Rise of Scientific Management (Madison: University of Wisconsin Press, 1980).

2 SUMMARY OF SITE VISITS

Members of the Committee visited five manufacturing companies now using computer-aided design and computer-aided manufacturing systems. These companies have all been leaders in using computerized automation and were in the process of integrating existing capabilities or implementing new integrated systems. The site visits were designed to gain a better understanding of data requirements, data flow, and linkage problems associated with these systems.

The companies visited were McDonnell Aircraft Company, Deere & Company, Westinghouse Defense and Electronics Center, General Motors Corporation, and Ingersoll Milling Machine Company. They were chosen to represent leaders in computer-integrated manufacturing (CIM) in a variety of industries, both defense and commercial, large and smaller companies, with product lot sizes ranging from one to many. There are, of course, other companies that have been leaders in the use of CIM, but the experience of these five companies covers a variety of products, company sizes, and corporate styles.

The Committee also met with the managers of the three major government programs that relate to computer-integrated manufacturing: the NASA/Navy Integrated Program for Aerospace Vehicle Design (IPAD); the Air Force's Integrated Computer-Aided Manufacturing (ICAM) program; and the National Bureau of Standards' Automated Manufacturing Research Facility (AMRF).

This chapter summarizes the information that the Committee collected as a result of its talks with industrial and federal managers. The results of the interviews are reflected in a broader context in Chapter 3.

DEFINITION OF COMPUTER-INTEGRATED MANUFACTURING

The companies visited agreed with the Committee's definition of computer-integrated manufacturing. As stated in Chapter 1, a manufacturing enterprise can be said to be integrated when:

- all the processing functions and related managerial functions are expressed in the form of data,

- these data are in a form that may be generated, transformed, used, moved, and stored by computer technology, and
- these data move freely between functions in the system throughout the life of the product,

with the objective that the enterprise as a whole have the information needed to operate at maximum effectiveness.

The companies stressed the participation of people in integration. They view CIM as a combination of computer-based data, automation, and people working harmoniously at a high level of effectiveness at all times. People are an important part of the system, which should be recognized in any definition of CIM.

The companies also spoke about CIM as involving continual flow of information among the several functions, such as that shown in Figure 1 of Chapter 1. Such a flow is required whether the integration of functions is occurring manually among people, automated via computer systems, or by a combination of the two.

INCENTIVES FOR COMPUTER-INTEGRATED MANUFACTURING

Each company visited viewed its business from both global and domestic perspectives and considered integration technology a primary need for supporting its business strategy. They all cited competition from foreign nations and a need to improve responsiveness to meet worldwide demand as a major strategic issue and incentive for CIM. One company noted that it was continually forced to improve on its own technology, which was being exported through offshore sales and through offset agreements that require production of parts and assemblies by foreign manufacturers. Demand for quality and responsiveness in the U.S. marketplace was another incentive. Each of these leading companies introduced computer integration only after serious consideration of the resources required, the risks, and the expected benefits.

The efforts in these companies focused on improving the information flow within the factory and particularly between the engineering design and production functions. The companies capitalized on the capabilities of computers to improve communication and control of the enterprise. The managers interviewed remain unsatisfied with the adequacy and timeliness of the information flow and believe that improvement in data communication will further improve corporate productivity and product quality.

PLANNING FOR INTEGRATION

Long-Range Planning

Each of the five companies has a formal plan for achieving CIM. Each plan has a broad, long-term perspective; in at least one of the

companies, the plan looks 10 years into the future. The companies set yearly objectives and budgets and measure progress toward those objectives.

These pioneers had to learn what has become obvious today: that it is enormously difficult to link heterogeneous groups of hardware and software. They now demand that new systems they acquire be able to link with existing equipment. The companies emphasized the need to create communication, understanding, and acceptance among people in various functions before expecting to succeed in automating the information flow among these functions. Their integration plans required a clear understanding of the information flow among the several functions.

Justification of CAD/CAM Integration

The companies visited generally had started their CAD/CAM activities in at least two separate areas. Automation of the engineering design process often began with computer-aided drafting and progressed to computer-aided design and analysis, while automation in production typically began with numerically controlled machines and evolved to computer-aided production facilities. These early efforts were often described as "islands of automation." As additional computer-aided technology was added, the need became clear to bridge the islands.

These companies independently concluded that the usual financial measures, such as return on investment, were inadequate for assessing the results of integration. These traditional measures have been useful for highly focused investments. In the integration of computer-aided technologies, however, both costs and benefits span multiple functions and are difficult to capture by traditional accounting procedures. The best measures, these companies say, are responsiveness, productivity, quality, lead time, design excellence, flexibility, and work-in-process inventories. Progress is also measured in terms of its consistency with corporate objectives.

Each company found that the introduction of coordinated CAD/CAM systems brought substantial improvements in productivity. A few examples:

- Printed circuit board assembly from design release to delivered product was reduced from 18 weeks to 4 weeks.
- Inventory was reduced from three months' supply to one month.
- By passing geometric data instead of drawings from design to numerical control programming, the man-hours per part programmed was reduced by well over one-third.
- A computer-integrated flexible manufacturing system reduced total personnel in routing, purchasing, torch programming, inspection, and machine operation by one half for the same output.

The companies studied have realized substantial gains cumulatively during the integration process. The values shown below are representative of the intermediate benefits of 10- to 20-year efforts. Further benefits are expected to accrue as full integration is approached.

Benefits Achieved

Reduction in engineering design cost	15-30%
Reduction in overall lead time	30-60%
Increased product quality as measured by yield of acceptable product	2-5 times previous level
Increased capability of engineers as measured by extent and depth of analysis in same or less time than previously	3-35 times
Increased productivity of production operations (complete assemblies)	40-70%
Increased productivity (operating time) of capital equipment	2-3 times
Reduction of work in process	30-60%
Reduction of personnel costs	5-20%

One large conglomerate¹ made a special study of the results achieved by a diverse group of independent companies through the modernization of production management systems. Production management systems are narrower than CIM, but the data indicate that significant savings have already resulted from the application of this portion of CIM technology. The findings of that study are in Appendix B.

Management Commitment to CIM

The direct involvement of top management was found to be the key to successful CIM programs in the companies visited. At one company, for example, systems designers were spending 60 percent of their time reconciling data bases, and action by the chief executive officer (CEO) was necessary to bring about change. He initiated a review of the data structure and data access needs and ordered a halt to new computerization during the two years necessary to create a new, unified data base. At another company, insufficient visibility of top management support caused the CIM effort to founder. With the creation of an executive vice presidency for technology, the company regained focus and direct involvement of top management in CIM.

Without exception, the senior managers selected highly competent people to plan and conduct their CIM activity and gave them clear authority, individual accountability, and a clear understanding of how their work linked to company goals. People on the CIM teams had informal, clear, frequent, and in-depth communication with the top management of their companies.

During the 20 to 30 years that these companies have been building the infrastructure for computer integration, they have learned a number of important lessons. Significant progress required the total commitment of strong technical staff and management teams. Managements had to learn, in the words of one, "to be smart, not sophisticated." The implication was that the existence of new technology did not necessarily mean that it was appropriate or necessary for the company to use it.

Progress toward CIM accelerated with understanding of the CIM plan at all levels of the organization and acceptance of the plan as a corporate goal. Good human relations and shared goals were a precursor for acceptance.

WHAT LEVEL OF CAD/CAM INTEGRATION WILL BE ACHIEVED?

The Committee attempted to discern whether the companies visited would achieve the level of integration described in our definition. The issue turned out to be not if they would, but when. Estimates ranged from five to ten years, based on today's perception of integration. Nonetheless, substantial technical, social, and financial barriers remain, as detailed in Chapter 3.

The companies visited expressed concern that they were in a small minority. With few companies making such efforts on a large scale, progress will be limited: the greater the number of companies working on CIM, the greater the benefits to all from shared experience. Furthermore, the large companies visited viewed the lack of CIM capabilities in their suppliers as an impediment to their own CIM plans. The few suppliers that had computer links to the company that did final product assembly were able to respond quickly to design changes.

All of the companies visited were faced initially with a relatively narrowly trained work force. They expressed a general need to provide improved training in new skills for nearly everyone, including the machine operator, the engineering work force, and the management team. These companies today have broad skill bases because of their extensive computerization effort over a long period. Other companies that undertake CAD/CAM integration will find the lack of skilled people one of their most serious problems. The availability of skills and training could very well determine how rapidly they can take advantage of this new technology.

STARTING A CAD/CAM INTEGRATION EFFORT

The more experienced companies have evolved their own methods of selecting, developing, and implementing CAD/CAM activities. The pioneering companies often underestimated the time and money required to learn how best to undertake these activities. Companies starting computer integration today can learn from the experience of the pioneers. The Air Force ICAM program has outlined key steps² for successful implementation of a CAD/CAM system at minimum cost. Information gathered on the site visits supports the outline:

1. Determine how the company is going to run its business in the future.
2. Determine the factors that will be keys to the success of this business in the future.
3. Develop a long-range plan that defines product evolution, rate of new product introduction, mission and objectives of facilities, and existing and planned capabilities.
4. If the previous steps have disclosed opportunities for improvement through development of CAD/CAM systems, the chief executive officer is then in a position to start the project.

In all of the companies visited, the CEO set up a multi-functional task force, led by a top level official. The functional representatives had departmental decision-making authority. This team determined the direction of the project, supported by internal and consulting expertise as required.

Industry is using several systems development cycles or steps today. One being used extensively was developed by the Air Force ICAM program and is called the Program Life Cycle.³ It guides the documentation of system development and has eight key steps:

- (1) Needs analysis
- (2) Requirements definition
- (3) Preliminary design
- (4) Detail design
- (5) Construction & verification testing
- (6) Integration & validation testing
- (7) Implementation & user acceptance
- (8) Maintenance & support

Companies take diverse approaches to CIM. Most of those visited started with narrow applications and gradually linked them to broaden the integration effort. The one company that planned to start by putting in place a comprehensive system found it necessary to abandon the effort and to work instead toward more modest, intermediate milestones.

Each company had different strengths on which to build. Most began with a pilot integration project in one division, typically the one with the greatest willingness to take the risk of making the

technological and organizational changes required for CIM. Managerial organization often is an impediment to computer integration, particularly if lines of communication do not exist among the appropriate parties.

FEDERALLY FUNDED CAD/CAM PROGRAMS

The three major federal programs directed at the integration of computerized systems in engineering design and production are directed at the solutions of problems that much of industry faces. No single program, however, has addressed the integrated system as a whole. Rather, IPAD addresses engineering design, ICAM addresses the architecture of manufacturing and the control of production, and the AMRF assists medium-sized and other companies to use shop-floor automation.

Federal technology programs tend to be reasonably applicable to many companies and therefore exactly applicable to none. Thus, companies seeking to integrate can find many useful technological accomplishments in these programs, but each company must customize its own integrated system. To the extent that these companies have access to information on technological accomplishments elsewhere, creation of a CIM system will be easier.

Integrated Program for Aerospace Vehicle Design

The initial objective of the Integrated Program for Aerospace Vehicle Design (IPAD) was to develop a computer software system for use by the U.S. aerospace industry in the design of future vehicles. This system was intended to reduce time and cost substantially and to foster improved vehicle performance.

The work began in 1976 at the Boeing Commercial Airplane Company with the preparation of specifications and preliminary design for an IPAD system. It was to support the full engineering activities of a large aerospace organization composed of many people working on many projects at several levels of design over long periods of time.

The project was broken into four phases:

1. Requirements for the IPAD program were defined by an examination of the aerospace design process and its interactions with manufacturing.
2. Integrated information processing requirements for aerospace design were established.
3. A software specification and preliminary design of a full IPAD system were prepared to support the requirements for aerospace design.
4. A partial version of the full IPAD system was developed, resulting in prototype software that demonstrated the feasibility and technology needs of data base management systems which could support the intent of a fully integrated system.

The requirements were for a general purpose: an interactive computer-aided engineering system capable of supporting engineering data associated with the design process and its interfaces with production. The system would serve management and engineering staffs at all levels, including the production processes.

The preliminary system design focused on a distributed, heterogeneous machine environment in which data base management technology and networks played critical roles in the total solution. In 1978, NASA decided to concentrate IPAD resources on two areas: data management and networking between heterogeneous machines.

Large improvements can be made in the way information is managed and shared, which IPAD demonstrated in its data base management system (DBMS) prototype, called IPIP. It is a multimodal, multiuser, multilevel schema, concurrent access DBMS that includes the data definition language (DDL) and data manipulation language (DML) required to solve engineering problems. IPIP supports multiple data models (relation, hierarchy, and network). These features promote a high degree of data independence.

The IPAD network system provides ultrahigh-speed exchange of data between heterogeneous equipment. It provides the equivalent of levels 3 through 6 of the International Standards Organization (ISO) seven-level model of communications. The system was the first to use Network System Corporation's Hyperchannel to provide process-to-process communications (levels 1 and 2 of the ISO model) between different computers (a VAX 11/780 and a CDC CYBER 835) using different operating systems.

In summary:

1. The IPAD studies of engineering processes provided a broad understanding of the system requirements that will have to be supported to reach integration.
2. The IPAD research work provided useful prototype software for advanced network communication and engineering data management, illustrating the nature of future products.
3. IPAD tutorials, reports, and applications established the advanced technology requirements of engineering data management, data schema, and integration of engineering applications with an engineering data management system.
4. The development of a software prototype helped stimulate vendors to produce new products in the areas of data management and network communications.

Recent NASA reviews of the projects led to the conclusion that IPAD had fulfilled to a large extent its original research objective. Consequently, NASA and Boeing are formulating a redirection of the project.

Integrated Computer Aided Manufacturing

While NASA and the Navy have sponsored IPAD, an engineering design system, the Air Force has sponsored the Integrated Computer Aided Manufacturing (ICAM) program, a production system. Both types of system are required for computer-integrated manufacturing.

Air Force studies in 1975 disclosed increased complexity of weapons systems, declining quality and productivity, and increased procurement lead times in much of the industry supporting Air Force procurement. In response to these studies, the Air Force created the ICAM program in 1976 to achieve major increases in productivity in aerospace batch manufacturing through widespread application of computer-based, fully integrated factory management and operation systems. ICAM had a nine-year budget of almost \$100 million. The demonstration of an integrated sheet metal center at Boeing Military Airplane Company in 1985 will culminate the program.

The Air Force approach was to create integrated management systems that tie all of the key production functions--product development, production, and product support--into a common data base. Production, the principal concern of ICAM, includes planning of facilities, assembly, fabrication, quality control, production control, inventory control, and data collection.

Early efforts were directed at identifying the key barriers to more effective integration. Through the use of industry/university consortia, ICAM then identified and demonstrated ways to break down these barriers in the industrial environment. Additional effort is directed at transferring the technology.

Product Definition Data Interface

Perhaps the most formidable technological barrier to CAD/CAM integration is the transfer of geometry and instructions across the design-production interface. The government program addressing this barrier most directly is the Product Definition Data Interface (PDDI) project within the ICAM program. It seeks to provide a framework for exchange of digital data defining the geometry of the product, which serve the function of the conventional engineering drawing.

The Initial Graphics Exchange Specification (IGES), managed by the National Bureau of Standards, established the initial base for direct digital exchange of graphics data. It has been adopted as a standard by the American National Standards Institute (ANSI Y14.26M, Section 2-4) and is being used by major vendors and users.

IGES provides a product definition data interface for limited applications. Full integration will require a complete product description that is accessible and understandable by users at all points in the manufacturing process. Advanced manufacturing technologies in numerical control, robotics, automated process planning, and inspection, and their integration into a cohesive system, are practically impossible if the product cannot be defined by digital data that can directly feed these processes.

The PDDI project is likely to extend the applicability of IGES considerably. Its objective is twofold, as shown in Figure 2. First, it will identify the current state of IGES implementation through the application of test procedures for current graphics systems. Second, it will define long-range manufacturing needs and demonstrate a prototype interface for product definition data that meets these needs. To these ends, the project will:

- analyze needs for product definition data in manufacturing, using sample aerospace parts
- define an automated framework for a Product Definition Data Interface
- develop a data format and utilities required to support the PDDI
- prove the concept of the PDDI through demonstration of the utility software

The PDDI prototype system is intended to serve as the information interface between engineering and all manufacturing functions that use today's blueprint, including process planning, numerical control (NC) programming, quality assurance, and tool design. It will be demonstrated with an advanced NC programming system and an advanced process planning system. The system also will be operated with two commercial CAD systems to demonstrate its general applicability.

Automated Manufacturing Research Facility

The Automated Manufacturing Research Facility (AMRF) of the National Bureau of Standards serves as an engineering "test bed" to supply U.S. industry with "new ways of making precise measurements of machined parts derived from NBS standards that will be developed using capabilities inherent in modern, computer-controlled machinery."⁴ A second objective is to encourage the modernization of U.S. industries through the development and common use of standard interfaces between various types of equipment.

Standard interfaces would enable heterogeneous components of a manufacturing system to communicate without a need for custom-designed interfaces. The challenge is to develop standard procedures, protocols, and interfaces that will support current and emerging technology without stifling innovation.

The AMRF seeks the most practical incremental route to automation for small to medium sized companies. It uses domestically built, commercially available machines, most of which involve two or more components made by different manufacturers. The modular, hierarchical software is believed by NBS to be the most flexible program available today. The program was first demonstrated in November 1983, and enhancements are planned over the next two or more years.

AMRF research is aimed at inspection of parts while they are being processed. With advanced machine-control systems and new computer technology, the computer can be programmed to compensate continually for known errors in machine movement, using sensors to determine

machine condition. An important question still to be answered is how to calibrate precisely a measurement process that is deeply embedded in the manufacturing process and that depends on the machine-tool control system.

Most large industrial firms now have heterogeneous computer-controlled equipment and the skills and resources to work out the complex interface problems of integration. However, 87 percent of discrete parts manufacturing companies have fewer than 50 employees.⁵ Smaller companies, with limited resources, cannot invest in large-scale automated systems all at once. Yet large companies that purchase parts from smaller companies find that their own CIM efforts are slowed by their suppliers' lack of CIM abilities.

Because the AMRF system is a research facility to be used by government, industry, and academia to evaluate different systems concepts, it has an emulation capability. Emulation is the ability to perform the computer functions of one computer or hardware element in another computer so that, from a logical basis, the rest of the system does not recognize the substitution. Any piece of equipment, group of machines, or subsystem can be caused to emulate another subsystem, so that the AMRF hardware and software can be used to evaluate a system using alternative choices of hardware and software.

NOTES

1. Richard H. Fabiano, General Electric Co., Bridgeport, CT.
2. Each of these steps is defined in detail in the Air Force document IDS150120000C, ICAM Documentation Standards, 15 September 1983.
3. Ibid.
4. Michael Baum, "Automated Manufacturing Research Facility (AMRF) Fact Sheet" (November 1983).
5. John A. Simpson et al, "The Automated Manufacturing Research Facility of the National Bureau of Standards," Journal of Manufacturing Systems (vol. 1, no. 1) p. 19.

3 ISSUES THAT INFLUENCE COMPUTER INTEGRATION

A number of issues can affect a company's willingness to pursue computer integration, the approach taken, and the likelihood of success. These issues can be categorized as technical, organizational, financial and accounting, and governmental. While many of the issues can be seen as barriers to computer-integrated manufacturing, recognizing them can provide opportunities to facilitate progress toward integration.

TECHNICAL ISSUES

Many problems perceived by organizations considering integration can be addressed with existing integration technology, but a number of technical barriers remain. Before computer-integrated manufacturing can reach its full potential for increasing productivity in both design and production, technical advances are needed in the following areas:

- data communication in a system in which both hardware and software are heterogeneous
- validation and consistency of data
- representation of integrated textual and geometrical data
- expert systems and artificial intelligence
- analytical models of manufacturing processes

These advances are listed in the probable increasing order of difficulty, but their relative importance will vary among companies, depending on company size and products. As the advances are realized, the implementation of the first three must be standardized within any organization if they are to be effective.

Data Communication

The data communication problem in CAD/CAM exists at three levels, as in many other complex computer systems. At the first level is communication between different programs running on a single

computer. This problem primarily involves data format and integrity and is not usually considered a communication issue. Companies small enough to be able to meet all their design, analysis, machine control, testing, and management needs with one computer will have only this level of communication problem.

The second level of communication problem occurs between computers of a single brand. Most large vendors of computers offer a mixture of hardware and software that allows some level of communication between their different products. The communication media can be chosen to meet the requirements of the factory, while providing the required control response times.

Most companies, particularly in manufacturing, use many different brands of computers because different types are better suited to different jobs. At one extreme are programmable logic controllers (which today are special purpose microcomputers); most of them are optimized for real-time on/off control of relays and motors, and their inputs come primarily from switches and other on/off sensors. At the other extreme are large mainframe computers optimized for arithmetically complex tasks or processing large files of data.

The third level of communication problem, then, is to provide communication among a variety of systems from many manufacturers. Such interchange can be achieved only if each pair of communicating systems uses a common protocol for communication control and representation of data. If the number of different systems (N) is large, then it is impractical for the vendor of each system to provide the $N-1$ specific protocols and keep up with any changes. Hence it is important to have a single protocol that each system can use to talk to all others.

The International Standards Organization (ISO) has defined a model for Open Systems Interconnection (OSI) that directly addresses this problem and is in the process of defining detailed standards for the required protocols. The National Bureau of Standards (NBS) and General Motors Corporation (GM) have been promoting, through separate but coordinated efforts, the implementation of these protocols by a number of computer vendors. The effort led by the NBS is sponsored by Boeing Computer Services and is aimed at demonstrating the compatibility of different vendors' implementations of a common protocol. The GM effort, called MAP (Manufacturing Automation Protocol), investigates the use of standard protocols to communicate manufacturing control files and status information among minicomputers and small systems like programmable controllers.

At the 1984 National Computer Conference, both systems demonstrated limited transfer of files among computers built and programmed by different vendors (Digital Equipment, Hewlett Packard, IBM, Motorola, Gould, and Allen Bradley). These standards will permit users to choose the best systems in terms of cost and application, while being reasonably confident that intersystem communication is possible. The GM effort is very important; it was gaining considerable acceptance by both users and vendors as this report was nearing completion and appears on its way to being a useful industry standard.

The NBS and others are working on procedures to test the conformity of individual systems to the protocol standards, so that eventual purchasers can have confidence that a mixed vendor system will work. A number of computer vendors whose products are used for graphic design, analysis, and management are also considering offering these ISO standard protocols.

Validation and Consistency of Data

The validity and consistency of data in a manufacturing data base must be assured if it is to be a reliable and comprehensive source of manufacturing information. Unreliable and inconsistent information is probably worse than no information. Traditional data processing has had separate data files for each application program. As a result, manual or automatic data translation between files has been needed, and data were often inconsistent. It is now widely accepted that data files should be separated from particular application programs by limiting data access with a common set of data management routines that preserve accuracy and consistency.

Validity generally means that all data entered into the data base obey any direct or calculated constraints imposed on them. This shifts the burden from the person or process entering the data to the formulation of the constraints, which must be accurate and tight enough to be effective, but not so tight as to inhibit legitimate change. Effective constraints will reflect models of product characteristics or process performance. One vendor has developed primitive automatic constraints on the designer, based on the capability of the production machinery and the material being fabricated.

Consistency means that a change in one data item is accompanied by changes in related data items. It is enforced by prohibiting the entry of inconsistent data or by recalculating dependent information. Although recalculation is feasible for simple constraints, in many cases the constraint calculation may require too much time, or the nature of the constraints may not be understood well enough to be expressed in current software technology.

Whether data are dependent or independent will depend on the point of view of the user. Part geometry, for example, is the independent variable from the point of view of the designer and dictates the process required to make the part; the manufacturing engineer, on the other hand, may view the available tooling as the independent variable that should constrain the part design. Most companies treat this as an organizational issue because techniques that provide for this multi-directional dependency are not yet well developed. Another consistency issue arises when changes by different people at different times are not coordinated.

Many of these problems can be handled with automated versions of existing sign-off or release systems. These systems, for example, allow only one individual to change the master copy of a design file; all other copies are considered unofficial working copies used at the

risk that the official version may change. The IPAD program began to deal with this problem in a distributed heterogeneous environment of computers and data base software.

Text/Geometry Integration

Most computer-based graphic design systems originated as more efficient ways to create conventional drawings. The intent was to provide efficient and accurate storage of enough information to recreate or modify a drawing; generally, no attempt was made to make the stored information usable by other systems.

As improved technology became available to analyze the functional behavior (e.g., strength, vibration, aerodynamics, heat transfer) of a mechanical part or assembly, it made sense to use the same data files for analysis that were used to generate drawings. This eliminated duplication of data entry and the possibility of inconsistency between the two data sets.

A further step is to use geometric information for production more directly--to use descriptions of sheet metal geometry, for example, to calculate die designs, or use descriptions of part geometry directly to calculate tool paths for numerically controlled machine tools, or calculate drill patterns for printed circuit boards directly from the file that defines the metal patterns. The objective is to extract the required information automatically from the computerized, graphical representation of an object.

If the information required by the production group is known in advance, algorithms (and therefore computer programs) might be constructed to obtain it from the model. However, the amount of semantic information carried by the graphical representation (and potentially required for fabrication) is very large; it is impossible to prepare in advance a sufficiently complete set of programs to answer all the queries that may come from the production group. Indeed, it is difficult to construct algorithms that yield answers to such simple queries as "what are the dimensions of the pockets to be milled?" or "which webs are thinner than 0.05 inch and higher than 0.5 inch?" It is quite difficult to construct a completely integrated CAD/CAM system in which the graphical representations of objects can be treated on a par with numerical or textual information whose semantics can easily be extracted as long as such data follow a prescribed format or syntax. The PDDI project is addressing the problem of making it easier to extract manufacturing process information from the design data base.

Currently, queries from the production group are handled by engineers looking at a drawing. These manual operations are a major impediment to the development of an integrated manufacturing system. Replacing them by a computer program will require considerable research, involving pattern recognition, scene analysis, graphic modeling, and artificial intelligence.

Expert Systems

The companies visited by the Committee viewed artificial intelligence as a long-term, not a current, need as they work toward CIM. Artificial intelligence is the part of computer science that is concerned with the symbol manipulation processes that produce intelligent action; intelligent action is goal-oriented and arrived at by an understandable chain of reasoning steps which are guided by knowledge of the world.¹ The most highly developed branch of artificial intelligence is expert systems. An expert system captures the knowledge of an expert in a particular area and transfers it to other users. A few such systems are now commercially available, though not for manufacturing problems. The lack of commercial products for manufacturing explains the present lack of demand for artificial intelligence.

Applied research is needed in building knowledge bases for selected manufacturing processes, especially in planning. Research is needed to clarify the issues of designing for manufacturability before an expert system for that purpose can be built. The concept of geometric reasoning is complex; it is difficult to create an expert system that can respond, for example, to the request to "find a symmetric object in the data base." A final research need for expert systems is to develop knowledge bases for making approximations in complex analysis problems.²

Process Models

More accurate mathematical models are needed for production processes, such as stamping, molding, cutting, grinding, or welding over a wide range of material or process parameters. Without them, engineers cannot perform the analysis and mathematical optimization of a process, nor attempt the synthetic construction of the process from the design data. Existing models tend to reflect the worst case. They do not indicate the real capabilities of a process under design and hence lead to far from optimum performance of the process in operation.

The primary problem in modeling many production processes is the lack of knowledge about or ability to control many of the important variables. As the importance of improving productivity increases and the cost of sophisticated measurement and control systems decreases, it will be feasible to use quantitative models to plan and control processes. The major research need is for a self-augmenting data base.

ORGANIZATIONAL ISSUES

Factors that are primarily a function of the modus operandi of an organization can affect the integration of CAD/CAM as much as the technical issues, if not more so. These issues can be categorized as:

- fragmentation and isolation of departments
- support of top management
- implementation uncertainty
- education and training

The history and geography of the United States and personal behavior patterns in U.S. society have a pervasive and lasting effect on the attitudes, responses, objectives, and approaches to problems and solutions that are found in manufacturing organizations. Our large domestic market and separation by oceans from other leading industrial powers has encouraged a tendency to ignore innovations in manufacturing technology in Japan, Europe, and the countries of the Committee on Mutual Economic Cooperation (COMECON), often to our disadvantage, until forced by the marketplace to acknowledge them.

Our society is heterogeneous, and the social structure is based on personal freedom, competition, and rewards--both monetary and in status--based on individual effort. The result can be a tendency toward adversarial relationships, such as are observed between labor and management, government and industry, line and staff, and even between groups within departments. One source of power in that adversarial process might be an individual's control of the data that a CIM system needs to operate.

Fragmentation and Isolation of Departments

Manufacturing organizations, as described in Chapter 1, have been progressively divided into separate and to some extent isolated departments. Decentralization in the past has proved useful to large organizations, as it dispersed decision-making and allowed each department to concentrate on its respective contribution to the manufacturing process. At the large organizations observed by the Committee, the benefits of decentralization may now be outweighed by the barriers it creates for integration.

The mass of data and the diverse data base structures, programming languages, computers, communications systems, and specialized hardware have presented groups with almost infinite numbers of alternatives. It is little wonder that these groups, seldom with integration or organizational standards as an objective, have made selections based on their internal objectives, which are not necessarily compatible with objectives across the organization. The longer a group goes without integration as a major objective, the more committed it is likely to become to its often unique configuration, and the more difficult integration becomes. The more diverse and isolated the groups within the organization, the higher the probability of problems and the more difficult their resolution.

Performance criteria, rewards, deadlines, and professional jargon are among the characteristics on which departments may differ. As a result, people in traditional organizations frequently exhibit loyalty to their individual disciplines and protect their turf to a degree that inhibits exchange of information and efforts to integrate. All too

frequently, they fail to view information, the data base, as a company resource--as valuable as money. Potentially even more damaging are groups that do recognize its value and restrict access through claims to ownership.

Organizational fragmentation and adversarial relationships can hamper the introduction of a new technology or a new product. These problems could prevent the introduction of computer-integrated manufacturing because CIM affects all parts of an organization. The solution, many companies have found, is to supplement reliance on the traditional hierarchy for coordination with the creation of project teams made up of representatives of the departments that contribute to the manufacturing process. Communication and problem-solving within a group that crosses departmental boundaries is a step away from fragmentation. Some form of team management was used for computer-integration efforts by all organizations visited by the Committee, even if only on an ad hoc basis.

Support of Top Management

Computer-integrated manufacturing is knowledge-intensive and affects all parts of an organization; therefore, its success requires the participation of all levels of the organization. The keystone is a unified data base, which may require years to realize. Without the commitment and understanding of top management and a top operations officer thoroughly committed to the concept, the coordination of changes throughout an organization cannot take place. In the company with the highest level of integration of those visited, the CEO actively supported the effort, even ordering a moratorium on new computing projects to stop proliferation of data structures while a unified data base was created.

The absence of a long-term strategic plan covering technology, marketing, finance, and integration appears to inhibit the adoption of CIM in many instances. Such neglect is frequently a result of management's failure to appreciate the corporate benefits from integration. Often these benefits are difficult to quantify, probabilistic, and longer term, whereas managers tend to stress factors that are short term and easily quantified. One result of the nature of the benefits is that it is not easy to know when to begin integration. A firm that does not do the proper systems engineering in advance might end up, not with the "islands of automation" suggested earlier, but with "reefs of automation" that actually slow integration because of the reluctance to scrap investments despite difficulties in linking those investments in a system. The recommendation of several executives was that the CIM plan come from the top down, implementation from the bottom up.

Implementation Uncertainty

Even with the assurance provided by top management support, integrating CAD and CAM produces great uncertainty for individuals and

organizations. When confronted with the unexpected, companies may be tempted to abandon all efforts rather than modify their plans. One of the companies visited was an instance of this phenomenon: an all-encompassing integration plan was dropped after the early milestones proved difficult to attain. That company is now reconsidering how best to approach integration.

Another impediment to integration is the likelihood that the transition will be uncomfortable, perhaps jeopardizing the power bases of key individuals. Integration will require changes in the management and control of organizations, even to the point of restructuring, and most people prefer to avoid the ambiguity and uncertainty that reorganization will be sure to bring.

An infrastructure that includes a basic understanding of systems, feedback control, computing, data base management, automated control, local area networks, and computer application systems is a prerequisite to successful integration. It is unusual in 1984 to find such an infrastructure in any but the largest or most progressive companies. A company can acquire it through training, but the breadth of training required may be costly and time-consuming. In addition, the necessary basic talents must be available. A good machine operator does not necessarily make a good NC programmer, nor are the characteristics that make a good manager of a labor-intensive job shop necessarily those required for an automated factory.

Even when a company has overcome these barriers and set integration as a goal, success is not assured. Several organizations that were studied had set such a goal and embarked on the program, but then lost sight of the original goal and settled for more limited objectives. This is not to indicate that integration should be an end in itself; it is a route to a more effective manufacturing system. Furthermore, it is a continuous variable, not binary or absolute; a company should attain the degree of integration that it can assimilate and not strive for 100 percent integration all at once.

Supply of Labor

The "factory" in this country is often perceived by managers and by the general public as a scene of labor-intensive activity, performed under dirty, noisy, sometimes dangerous conditions, and best avoided if at all possible. It is too often assumed that if finance, marketing, and product engineering perform their functions, production will take care of itself with little or no attention from top management: that production really doesn't require many important decisions and return-on-investment calculations will adequately cover them. Skinner has pointed out how inaccurate these impressions can be,³ and entire industries, such as consumer electronics and appliances, cameras, and motorcycles, have already suffered from reliance on such calculations.

Long-held beliefs have lives of their own, however, and the image of production still limits the creativity and manpower applied to the solution of production problems. Students who might otherwise be interested generally prefer the prestige and challenge of a career in

engineering or management with the result that few U.S. universities offer degree programs in manufacturing. Not long ago, more students of manufacturing were enrolled at the University of Stuttgart, or Dresden, or Karl-Marx-Stadt, than in the entire U.S. higher education system. People in many countries see manufacturing as a prime source of improvement in their standard of living, and careers in manufacturing as prestigious and satisfying.

Society's main concern about automation is the threat of unemployment. However, while the level of automation has increased significantly over the past 200 years, it has increased incrementally. Unemployment levels averaged over a period of years have stayed at about six percent. If the technological changes now under way raise unemployment to a higher base, the problem must be faced by society in both human and economic terms.⁴

Manufacturing has always required a variety of skills for the production of any item; further, the amount of effort expended varies from one skill category to another. As manufacturing progressed from a handcraft to today's high technology, these skill categories have changed and their relative proportions have varied.

The past century has seen the virtual elimination of tasks requiring mere physical strength; during the past half century, automation has greatly reduced the tasks requiring full-time manual control by a worker. As a result, the number of people employed in "direct" labor has been declining. Those who could not learn any other skills became unemployed. The displacement has been incremental over the half century, however, and society has accepted, and partially adapted to, this erosion of the number of manual workers. Direct labor is now such a small percentage of the total cost of production that it is a small target for further automation, relative to other possibilities.

The past decade has seen the transfer of tasks requiring mental skills for the control of production machines, or for the management of work flow in the factory, to data processing equipment. Again, the number of those employing mental skills in the direct control of equipment has diminished. However, the number of those employed in preparing the body of knowledge for execution by the data processing system has increased substantially. Similarly, the skill required to supervise the operation of a computerized system, and the number so employed, have also increased.

The experience of this past decade suggests that most workers using mental skills could be retrained to prepare and control computerized equipment or to perform some other function requiring mental skills. Because of their better educational foundation, they are easier to retrain.

The transition to CIM technology, therefore, should not in the future have a profound effect on the level of employment in an enterprise. It is hoped that the enhancement of productivity, quality, and speed of response to the market's demands will halt the emigration of industrial production to other countries, thus sustaining or improving the overall level of industrial employment in this country.

This optimistic view will be realized only with nationwide acceptance of this fact: Workers in the industry of the future must enter industry with a higher educational level, and with different skills, than today. They must accept the certain knowledge that skill requirements will continue to change at an ever increasing pace. The applicability of an industrial entry-level education is today less than half the expected working life of the entering worker. Educational updating of those employed in manufacturing will be an essential routine throughout a worker's employment.

FINANCIAL AND ACCOUNTING ISSUES

The United States emerged from World War II relatively unscarred and in a strong economic and military position. We had a large backlog of domestic consumer demand and technology, as well as readily available labor. The subsequent years were an ideal time for firms to grow and prosper. Anything that couldn't be sold domestically found ready world markets. Many began to believe that the U.S. industrial base was indestructible and that its fruits should be broadly shared.

Political circumstances dictated a shift from military and investment spending to social and consumer spending. Taxes and labor costs increased. Many manufacturers attempted to maximize profits by offshore production and emphasis on short-term payoff from investment, often using cash payback or return-on-investment (ROI) calculations as the sole criterion.

In a financially and technologically stable environment, emphasis on short-term criteria may lead to the highest profits, and firms that took this approach flourished for some time. During this period foreign competitors, sometimes fueled by national consensus and government support, invested aggressively in manufacturing facilities and technology. In the process, they took advantage of the dramatic decline in the cost of computer hardware relative to performance.

In this economic context, the need for new financial models is clear. By models we mean the quantification of the appropriate variables and establishment of relationships among them to describe a situation and facilitate making decisions about it. The area that particularly demands improvement is evaluation of investments, particularly in new technology.

In the past, ROI has been effectively used almost as a standard procedure by much of industry. Companies undoubtedly face situations, such as the comparison of projects for capital investment, in which ROI and other strictly financial measures are still useful. ROI, however, at least as presently used, is clearly not the appropriate method for making decisions on investments in new technology. Until a generally acceptable method is available to measure the long-run effects of investments in technology, the introduction of flexible automation and integration will suffer.

ROI methodology assumes stability in the economy, technology, labor, and, most important, the marketplace behavior of competitors--assumptions that have proven time and again to be false. In addition,

it stresses short-run returns rather than long-run strategy. No adequate effort has been made as yet in this country to remedy the situation. If the true costs and benefits could be included, ROI would be appropriate for determining the value of investments, even those as complex as computer integration of factory information. The difficulty lies in the disparity between the apparent ease of quantifying costs and the difficulty of quantifying benefits.

The result has all too frequently been the following scenario. A new technology becomes available, but its costs (including education of workers) and the uncertainty of the benefits result in an unacceptable ROI. As refinements and enhancements of the technology become available, the investment is successively less cost-effective because of the higher costs associated with overcoming the ever-widening infrastructural gap. For some years, the company's failure to invest in the technology poses no significant problem because most of its competitors are following the same path. Then, other firms, perhaps foreign, begin implementing the new technology, even incurring early losses to do so. At some point these firms are able to reduce their manufacturing costs, which, coupled with stable market prices, enables them to generate sufficient funds for technological innovation and expansion, each stage built on a sound prior base. The innovator is often able to cut prices and increase market share, sometimes driving its competitors--with their outdated technology and facilities--entirely out of the market. Unfortunately, the emergence of a gap in manufacturing technology is not a single, epoch-making event, easily noticed, but a continual process that slowly erodes the foundation on which the firm operates. While ultimate collapse may be avoided, the U.S. manufacturing sector has not only lost once-viable firms through this process, but is on the verge of losing entire industries as well.

The challenge for research on financial and accounting analysis techniques is to accommodate risky investments as a cost of long-term survival. Prof. Robert Kaplan reports⁵ that a theory now being explored would support investment on the basis of a combination of financial measures and such nonfinancial indicators as quality, inventory levels, productivity, delivery lead times, new product launch times, new product characteristics, employee training, employee morale and promotions, and customer and supplier satisfaction. While these factors are difficult to measure and, therefore, are seldom if ever included in traditional analyses, they are essential to the strategy of companies aiming to be world-class competitors.

The Committee found in its interviews that the most common driving force for integration of information was actual or threatened loss of market share. If loss of market is the signal to begin improving manufacturing technology, however, the response frequently begins too late for the firm to recover. The message is clear: companies that face competition, particularly foreign competition, must have current manufacturing technology or risk cataclysmic consequences.

The United States, like other industrial societies, has gone through phases of abilities fundamental to its well-being. Years ago, the successful firms were those that could make products. Later, the

ability to invent or design products became more important. Next, the important consideration became the ability to aggregate demand--to expand the market--so as to achieve economies of scale in production. The emphasis then shifted to finance and conglomerates.

The widespread use of the digital computer in industry marked the dawn of the information phase, where the factors important to success include the ability to generate, transmit, maintain, and use information in operational and control activities. This phase influences every aspect of a company's operations. Individuals within organizations may have to adapt to quite different functions and responsibilities. If technological changes are evolutionary, the costs will be small and incurred over a long time. If they are revolutionary, the time will be short and the costs may be high enough to force some companies from the marketplace. To remain competitive, companies must invest in training, a factor that is rarely included in financial analyses, but has an obvious impact on a firm's viability and long-term options.

Many companies have compensation schemes that do not adequately reward individuals for integration, cooperative activities, and projects with long-range payoffs. In fact, most corporate incentive plans are oriented toward short-term profits rather than attainment of strategic goals.

Clearly, either a more comprehensive method must be developed for guiding investment decisions, or decision-makers must be found who have both sufficient strategic knowledge of their firms and the backbone to break the viselike grip that ROI calculations currently have on management.

The Japanese do not have the same commitment to ROI. It was reported recently, for instance, that the Seibu group has built a robotic grocery store in Nomidai, which the company president admits "will not be profitable by itself." It is the prototype for a fully automated store he plans for 1985 in the Tsukuba Science City north of Tokyo.⁶ A corporation has to invest in technology before reaping its benefits, and ROI calculations do not capture all those benefits. It is noteworthy that none of the firms the Committee interviewed mentioned ROI calculations as significant in its decision to undertake integration.

GOVERNMENT ISSUES

The federal government is not only a large purchaser of manufactured goods, but also has a vested interest in the benefits of a strong manufacturing sector throughout the economy. The goods-producing sector of the economy creates the basic, tangible wealth of a nation, the wealth that ultimately supports the entire economy.⁷ The services sector contributes to the standard of living and quality of life, but is itself dependent on the goods-producing sector.

In the United States, manufacturing accounts for two-thirds of the goods-producing sector of the economy, with the other one-third divided

between the extractive industries (agriculture, fishing, and mining) and construction. Thus, improving the cost-effectiveness of manufacturing has tremendous potential for improving economic and social well-being in this country. Computer-integrated manufacturing has demonstrated its ability to improve cost-effectiveness, even at its early stages of development.

Yet the government in its own activities has not promoted CIM or required its contractors to use it, either through contract specifications or by establishing industrial standards. The government has recognized the need for improved manufacturing technology for military systems, as demonstrated by its Manufacturing Technology (ManTech) program. Commercial manufacturing has similar needs, but not such a beneficial program. We believe that government should encourage--rather than discourage--cooperative efforts in integration techniques in commercial as well as military manufacturing.

The government is the nation's largest purchaser of manufactured goods and in this role can provide leadership through purchasing specifications (as was done with numerical control of machine tools), lending capital equipment, requiring technology transfer on projects, and assisting industry in the development of standards. There is always a trade-off in the establishment of standards: if it is done too early, performance will be restricted and the full benefits of the technology never realized; if it is done too late, changeover costs will be so high that standardization will be impracticable. The U.S. manufacturing community generally believes that standards should be set as a result of usage, and that is it too early to consider standards for CAD/CAM or factory communications.

The FEDD (For Early Domestic Dissemination) clause limits the use of the results of research or developmental projects funded by the DOD. It permits the distribution of the results of the projects within the United States, but prohibits their export to foreign parties. This provision precludes the use of the material in teaching or collegiate research where foreign students might attend a course or work on a research project. Nor can a professor publish any work that incorporates material subject to the FEDD clause. Thus, the diffusion of new technology from DOD projects carrying FEDD clauses is substantially curtailed. While the establishment of the FEDD clause was motivated by concern for national security, we believe that the DOD should consider dropping the clause to improve the technology of its industrial base.

Finally, the government can play a role by reducing the risks of technological innovation in manufacturing. This can be done indirectly by creating an economic, legal, and social environment that is conducive to and stimulates risk-taking; or it can be done directly through government programs that support technological innovation or the direct financing of high-risk or generic research.

NOTES

1. D.R. Brown et al, R&D Plan for Army Applications of AI/Robotics (SRI International, 1982).

2. Committee on Science, Engineering, and Public Policy, "Report of the Research Briefing Panel on Computers in Design and Manufacturing" (Washington, D.C.: National Academy Press, 1983), p.60.
3. Wickham Skinner, Manufacturing in the Corporate Strategy (New York: John Wiley & Sons, 1978).
4. "The Process of Technological Innovation: Reviewing the Literature" (National Science Foundation, May 1983).
5. Robert S. Kaplan, "Accounting and Control Systems for the New Industrial Competition" (Working Paper, Harvard Business School, November 1983).
6. Geoffrey Murray, "High-tech bean-stockers invade Japanese supermarket." Christian Science Monitor (April 5, 1984), p.9.
7. "The National Role and Importance of Manufacturing Engineering and Advanced Manufacturing Technology" (Position Paper by the Society of Manufacturing Engineers, Dearborn, Michigan, May 1978).

4 RECOMMENDATIONS

The recommendations that follow are based on the need to support progress in factory data management techniques and increase the use of CIM in response to the declining competitiveness of the U.S. manufacturing base. It is estimated that fewer than 1,000 U.S. companies are seriously pursuing CIM efforts. One objective of these recommendations is to ensure that the companies considering or just beginning a transition to CIM have access to the knowledge already gained by those few manufacturers that have in some cases as much as 20 years of experience with the concept. A second and more significant objective is to ensure more collective action than has occurred to date in implementing CIM. Implementation of CIM is beyond the capabilities of most individual manufacturing organizations. This fact implies the need to develop and disseminate knowledge on factory data management issues by both industry and government working toward the same ambitious goal--CIM more widely applied in U.S. manufacturing.

1. The Committee recommends that the National Aeronautics and Space Administration adopt a strategy of computer-integrated manufacturing for its Manned Space Station program.

Major programs that NASA undertakes have limited schedules and budgets, rely on unproven product technologies, and operate in an environment where quality is critical. These circumstances point to an increasing need to automate design and production operations to achieve program goals. This Committee believes that the Manned Space Station program is not only a logical but an essential place for NASA to initiate a concerted computer-integrated manufacturing effort.

The use of CIM for the Manned Space Station is essential to meeting the program's administrative goals--a manned station in space in 1992 at a total cost of \$3 billion--because manual coordination of the data to support the design and manufacturing of systems components would be time consuming and prone to error. Adoption of a clear CIM strategy by NASA would avoid the evolution of incompatible approaches as each manufacturer or supplier prepares to respond to NASA's space station requirements. Unless the efforts of the hundreds of companies supporting the space station program are coordinated by means of CIM, design engineering and production errors are likely to proliferate.

Finding and correcting these errors would entail substantially higher costs, longer development time, and perhaps reduced operational capability.

Because many components in the space station will be unique or produced in small batches, the most obvious benefits of CIM would be realized in engineering design. However, including production in the CIM system would provide a significant measure of flexibility in the project configuration and would ensure high quality.

A secondary reason for the use of CIM in the Manned Space Station program is to further the development and use of the technology. NASA has a legitimate role in sponsoring the development and diffusion of technology, such as CIM, that is important to the country but that initially, at least, is beyond the resources of a single company to deliver. The Apollo and Space Shuttle programs provide clear precedents for NASA-funded creation and diffusion of new technologies.

NASA can influence a large portion of U.S. industry because the program will involve many companies, in both aerospace and other manufacturing sectors. Investment in technologies such as CIM is driven by the marketplace; with an \$8 billion space station program, NASA will be a powerful market force. The program managers will need to plan carefully to use that power constructively.

Adoption of a strategy of computer-integrated manufacturing would require implementation of CIM throughout the pertinent operations of both NASA and its contractors. Such an effort would involve many combinations of computer equipment from various vendors. To permit communication among these heterogeneous systems, NASA would have to adopt standards for data definition, data formats, languages, and protocols. The communications problem would be difficult but, in the Committee's opinion, surmountable. In solving it, NASA could draw on four existing federal efforts: the Integrated Program for Aerospace Vehicle Design (IPAD), funded by NASA and the Navy; the Air Force's Integrated Computer Aided Manufacturing (ICAM) program; the Product Definition Data Interface (PDDI) effort under ICAM; and the National Bureau of Standards' Automated Manufacturing Research Facility (AMRF).

NASA also could benefit from the experiences of companies now well along in implementing CIM. From information supplied by five such companies, the Committee has extracted a set of guidelines for CIM programs (Table 1, at the end of this chapter). Although the guidelines are oriented toward industry, they are applicable in important respects to NASA. They indicate, for example, that to implement an effective CIM program, the Administrator would instruct the manager of the space station program and the directors of the NASA laboratories involved to prepare a master plan. Execution of the plan would be directed by the Administrator through the program manager and laboratory directors. The Administrator also would direct efforts to take full advantage of the experience of companies who have been implementing CIM.

2. The Committee recommends that companies form consortia to pursue research and other projects in CIM not readily undertaken by individual companies.

The technological accomplishments required to achieve CIM entail enormous expense, creativity, planning efforts, and amounts of time. Only the largest U.S. manufacturers, or those responding to a specific marketplace requirement for CIM, can be expected to apply the needed resources to their CIM efforts. Yet the Committee believes that a majority of U.S. manufacturers will not be able to remain competitive in the quality, timeliness of delivery, and cost of their products unless they use CIM. Therefore, cooperative efforts among companies will enable a broader base of U.S. industry to achieve CIM.

The companies that have started using CIM have created their own systems. It will be some time before the technology is sufficiently advanced and potential users sufficiently sophisticated for vendors to sell CIM systems. At present, user companies still need to do their own development, a task that is beyond the capabilities of many smaller companies that need CIM to remain competitive.

To speed the rate of application of existing knowledge about CIM, and to identify priorities for research, groupings of companies should organize to pool their efforts. Individual company applications of CIM technology will vary in hardware, software, and order of implementation. However, many issues in data communication, data bases, and process modeling surpass the abilities of single companies and could best be resolved cooperatively. The Department of Commerce's R&D Limited Partnership program may offer a useful mechanism for forming consortia. Any company that purchases a large number of manufactured components is a candidate for a cooperative effort.

As a specific instance, the Committee recommends that the automotive industry--auto producers and their principal suppliers--embark on a joint program of development and implementation of techniques and standards in the area of CAD/CAM integration. This activity might be carried out by the Automotive Industry Action Group (AIAG), a nonprofit industry association that is disseminating just-in-time technology to the industry's suppliers, or by another consortium with comparable legal and support arrangements. The automotive industry already is pursuing a number of elements identified in this report (GM's Manufacturing Automation Protocol, the IGES standard, and component releasing/shipping/inventory systems), but further work is required to extend communication standards to the CAD area, to technical vendor/customer communication, and to manufacturing data bases.

In the spirit of Recommendation 2, the Committee believes that companies and industrial sectors should build close working relationships with universities in education, research, and technology transfer related to CIM. Industry also should seek analogous relationships with the relevant federal programs, drawing on ICAM, IPAD, and the AMRF for appropriate technology.

3. The Committee recommends that the Computer and Automated Systems Association compile knowledge of CIM technology, drawing on both industrial and governmental sources, and make it available to industry, to universities, and to governmental agencies.

All of the companies involved in the Committee's site visits had spent a good deal of time planning and organizing for computer-integrated manufacturing. Companies that are not as far in their thinking about CIM should not have to develop their plans from scratch. If existing information were available in an organized form from a central place, diffusion of CIM technology would accelerate. The intent of this recommendation is that existing information on CIM be collected, organized, and disseminated to current and prospective users. New information would be added as it became available.

The Computer and Automated Systems Association (CASA) of the Society of Manufacturing Engineers has the constituency, mandate, and authority to carry out this recommendation. CASA's membership comprises engineers with an interest in and experience in computer-integrated manufacturing.

Although some of the information developed by the leaders in computer-integrated manufacturing is proprietary, much of it is not. The availability of such information in well organized formats could be extremely helpful to manufacturers who are interested in CIM but lack the resources to initiate and develop programs unilaterally. Adoption of Recommendation 1 would create a large demand for this type of information.

Detailed understanding of CIM resides largely in industry, and progress in the field has outpaced our universities' ability to play their traditional roles--research and teaching--in this area. Curricular materials in the field are extremely scarce. Effective efforts to make current information on CIM readily accessible to faculty members would yield important benefits and, in the long range, are probably indispensable to the nation's well-being.

4. The Committee recommends that the federal government continue to undertake research to resolve fundamental technical issues related to computer-integrated manufacturing.

Resolution of the technical issues in Chapter 3 requires more research than a single company can undertake on its own. Data communication in a heterogeneous system, validation and consistency of data, representation of textual and geometrical data, expert systems, and analytical models of manufacturing processes are all risky areas of research, requiring multiyear, cooperative efforts. Solutions to these problems are needed to advance work in computer-integrated manufacturing.

We believe that the national research agenda should be revised to incorporate these needs and that the efforts initiated should be given long-term support. The Federal Coordinating Council for Science, Engineering, and Technology, chaired by the President's Science Adviser, might be the appropriate group to manage federally funded

research related to CIM. Federal science policy-makers need sufficient understanding of the generic research issues outlined in this report so that a small percentage of the federal research budget can be effectively directed toward building the cumulative knowledge base necessary for progress on these issues.

As this report states, the federal government can be pleased with the results of its initial modest investments in CIM technology. In the past 10 years, the Air Force and NASA have sponsored the two largest government programs that have furthered technological developments in support of CIM. While the Air Force's ICAM is concluding by tying its findings together in the demonstration of a sheet metal center, the NASA IPAD program has ended without any such wrap-up. IPAD's use of Hyperchannel was a step toward communication between heterogeneous computers, and the program had begun to extend its work to the transfer of geometric data within heterogeneous systems. It would be a shame to lose this valuable research; it should remain on this country's agenda of research related to CIM.

5. The Committee recommends that federal agencies that purchase manufactured goods accept digital data sets compatible with the Initial Graphics Exchange Specification, rather than requiring conventional drawings, as a deliverable item under contracts.

This recommendation applies to all federal agencies that procure manufactured goods with high tolerance specifications and require the ability to replicate these products. These agencies include NASA, the Departments of Defense and Energy, and others.

Some federal contractors already handle graphical material internally in the form of digital data and create conventional drawings solely to satisfy federal contracts. Besides the inefficiency of this procedure, errors that creep into drawings produced only to satisfy contracts may not be found until another contractor tries to use the drawings. Acceptance of digital data by the government would obviate this problem and, more importantly, would promote the creation of computer links between organizations as well as within them.

The government's acceptance of digital data, instead of drawings, as a deliverable item under contracts would also increase the market demand for CIM technology and expedite the transition to computer-integrated manufacturing in this country. The requirement for data in a form compatible with the Initial Graphics Exchange Specification (IGES) is recommended because IGES is the only communications protocol as yet widely accepted in industry. It establishes an initial basis for direct digital exchange of graphical data and has been adopted as a standard by the American National Standards Institute.

Although IGES currently applies only to limited situations, it is an important first step in accepting digital data. Enhancements to IGES should result from current research such as the Product Definition Data Interface (PDDI) project. PDDI is based on IGES,

thereby reducing the risk of system obsolescence. As enhanced versions of IGES or other digital standards gain acceptance in industry, they should also be used by federal agencies.

6. The Committee recommends that manufacturing companies considering investment in product design or manufacturing process technology consider computer-integrated manufacturing.

Adoption of CIM technology is essential to the maintenance or recovery of competitiveness by U.S. manufacturers in domestic and world markets. Companies regularly find themselves losing ground to competitors who are introducing CIM. Nevertheless, far too few companies in this country are working seriously to adapt the concept to their operations.

Companies that are about to invest in product design or manufacturing process technology should be aware of the potential benefits of CIM, as well as the consequences of postponing the decision to plan and gradually implement an integrated system. Competition in manufacturing can only become more intensive--witness the considerable development effort abroad (Appendix C)--and companies that do not move into computer-integrated manufacturing, the Committee believes, face a dim future. The necessary extent of the top executive's involvement in such a transition is suggested by the guidelines in Table 1.

TABLE 1
GUIDELINES FOR CIM

Each organization must create and execute its own plan for computer-integrated manufacturing, but the experiences of companies that have done so successfully indicates that the following guidelines are generally applicable.

Management Guidelines

- The chief executive officer (CEO)* decides whether CIM is the right technology for his organization, makes the decision to invest in CIM, and gives the transition his full support. Because computer-integrated manufacturing cuts across organizational boundaries and affects all people in an organization, these decisions must be made by the CEO.

- The CEO bases his decision on performance goals, such as reduced work-in-process, increased market share, and quality. Conventional justification methods for investments cannot capture the benefits of CIM, which are cross-cutting and difficult to measure.

* In conglomerates, the highest executive in a business unit will be more appropriate than the literal CEO.

- The CEO directs the development of a companywide, long-term plan that will guide the CIM effort; the plan includes yearly targets, budgets, and measures of performance.
- The CEO assigns a senior executive, reporting directly to him, to manage the CIM effort.
- To work under the CIM manager, the CEO assembles an interdisciplinary team of highly competent people from all areas of the organization.
- The CEO ensures that employees at every level in the company understand and support the CIM plan. Good communications must exist among people before computer integration of their areas of responsibility is possible.
- The CEO recognizes major barriers to CIM--adverse labor/management relations, financially oriented managers, and a narrowly trained work force--and takes steps to mitigate them.
- The CIM manager implements the plan gradually, adjusting the pace of adoption to the company's ability to assimilate change.
- The CIM manager seeks opportunities for cooperative efforts where appropriate--with universities for technology transfer, education, and research; with national efforts such as ICAM, IPAD, and the AMRF; and with professional societies to share knowledge, educate employees, and encourage common data communication standards.

Technical Guidelines

- Define and locate data bases shared by product engineering and design, production engineering, and production operations.
- Define protocols and conventions used in data definition and handling. The evolving IGES standard and results of the PDDI working groups are suggested as guides.
- Recognize that machine tools, computers, and other engineering and production equipment are parts of a total system, and select and maintain them accordingly.
- Establish as a goal of the integrated system the ability to use hardware and software from any supplier.

APPENDIX A
INTERVIEW QUESTIONNAIRE

I. DEFINITION

We understand "integration" to mean: having an information structure supporting a free flow of all information resident in the system to any part of the system as needed. The information stream can continually grow and be enriched while supporting all required functions throughout the organization and during the life of the product.

Functions supported include finance, marketing, sales, quality, product engineering, and production operations. The committee is mainly concerned with the relationship between product engineering and production and the improvement of communications and understanding on both sides of the interface.

1. Do you generally agree with the definition and is this a key objective in your company plans?
What role does the design-manufacturing interaction play?

II. THE PLANNING PROCESS

2. Why are you pursuing integration? How does it serve your business plans?
3. How did you plan and organize for integration?
4. What is the scope of your integration project? Does it include organization elements outside of design and manufacturing production?
5. How long do you think it will take to essentially achieve integration?

III. EXECUTION OF THE PLAN

6. What start-up problems have you encountered?

7. Were there efforts that were easily or quickly achieved?
8. Do you have any unique circumstances that have affected execution of your plan?

IV. DATA BASE CONTENTS

9. How much of the design is done through use of CAD? That is, what part of design output is represented digitally compared to drawings?
10. Have you found it necessary to use artificial intelligence in order to effectively access or couple data bases?
11. How is change control maintained in design and manufacturing production? Who is allowed to introduce changes?
12. Is the master schedule directly tied into the CAD/CAM data base so that design changes are automatically communicated to the production organizations?

V. ORGANIZATION

13. Have you changed or do you plan to change organizationally as a result of your integration efforts? How do you judge the effect of such changes on company or division performance?
14. Have you found it necessary to provide special training?

VI. MEASURES OF PROGRESS

15. Will you meet your objectives as perceived in the plan? On schedule?
16. How do you measure progress? Are the perceptions different at various levels or parts of the organization?

APPENDIX B CIM TODAY

This appendix provides supplementary information on what has been accomplished in computer-integrated manufacturing and the directions it can be expected to take.

SHOP FLOOR INTEGRATION TODAY

Integration across the CAD/CAM interface is in a rudimentary state today. Flexible manufacturing systems (FMS) represent the current state of hardware integration. The most advanced of these FMS's consist of automated machines, equipment, and work- and tool-transport apparatus, all operating under computer control with minimal manual intervention. They contain all the production equipment and production process modules of the CIM system represented in Figure 1 of Chapter 1, as well as production control software and even a modicum of production planning software. Experience with FMS provides some actual performance data on the benefits of integrating part of the total system of manufacturing.

An example will illustrate the striking benefits achieved. A flexible manufacturing system, described by Dronsek,¹ has been operating for several years at Messerschmitt-Boelkow-Blohm (MBB) in Augsburg, West Germany. The basic elements of this system are: (1) 25 numerically controlled (NC) machining centers and multispindle gantry and traveling-column machines, (2) fully automated systems for tool transport and tool changing, (3) an automatic guided vehicle workpiece-transfer system, and (4) integrated hierarchical computer control of all these elements.

The automatic workpiece-transfer system brings workpieces to and from each machine tool, for operator setup, by means of computer-controlled carts. The automatic tool-transport-and-tool-changing system brings tools to each machine via an overhead transport system. It then transfers the tools to a continuous elevator tool-storage system, which in turn provides them to the automatic tool-changing mechanism of the machine tool. All three of these subsystems--the machine tools, the workpiece-transfer system, and the tool-transfer system--are coordinated, controlled, and automated by a hierarchical

distributed computer system. The system is controlled by computer numerical control (CNC) and operated by direct numerical control (DNC).

Recently MBB compared the performance of this integrated system with the projected performance of unintegrated (stand-alone) NC machine tools doing the same type and quantity of work. The integration had reduced the number of NC machines required by 52.6 percent, personnel required by 52.6 percent, floor space required by 42 percent, part throughput time by 25 percent, total production time by 52.6 percent, tooling cost by 30 percent, total annual costs by 24 percent, and capital investment costs (including all the additional supporting and peripheral equipment and software required to accomplish full integration) by 10 percent. This last fact alone illustrates that CIM can free large amounts of the idle capital associated with machines that are normally underutilized.

MBB also has experienced nonquantifiable benefits as a result of this level of integration. Improvement in product quality has been realized in the form of higher accuracy and reproducibility, lower rework costs, and lower scrap rates. This quality improvement in turn has resulted in lower quality-assurance costs. Production schedules are more predictable, and the typical level of paper flow has decreased. Furthermore, working conditions have improved owing to the decreased risk of accidents, the relief from heavy physical labor, and the more challenging nature of the work. Finally, and most importantly, increased flexibility has made the manufacturing operation essentially independent of batch size, of the types of parts, and of production quantities: sets of parts can more easily be produced just in time for assembly, thus reducing the inventory of parts in process.

The FMS, as an element of the computer-integrated factory of the future, demonstrates that automation can be essentially free if properly designed and utilized. First, a much smaller number of automated workstations is required because of higher utilization. The capital saving more than pays for the additional integrating facilities, including software. Secondly, the ability of these systems to produce parts as required for immediate assembly reduces work-in-process inventory, freeing capital and reducing interest costs. The just-in-time production made possible by flexible automation allows a plant to turn its total inventory more times per year than is normal in a conventional factory.

None of these advantages, however, may be realized in the absence of another set of factors: the foresight, courage, and commitment on the part of management to recognize the opportunity, to accept the risks of a new production method, and to stick with the planned course of action until the goal is achieved.

BENEFITS OF SELECTED APPLICATIONS

One large conglomerate² made a special study of the results achieved by a diverse group of independent companies through the modernization of production management systems. Production management systems are narrower than integrated CAD/CAM, but the data indicate that significant savings have already resulted from the application of this portion of CIM technology.

Product/ Industry	Application	Result
Manufacturer of Components for Computer Peripherals ³	Material Requirements Planning	<ul style="list-style-type: none"> o 25% Reduction in Production Time o 50% Reduction in Work in Process Inventory o 30% Reduction in Parts Inventory Value
Manufacturer of Machine Tools ⁴	Material Requirements Planning	<ul style="list-style-type: none"> o On-Time Shipments went from 77% to 93% o On-Time Production Schedule Completion from 85% (Measured Monthly) to 100% (Measured Wkly) o Productivity from 62% to 68% o Manufacturing Past Due Hours from 11,000 to 1,900 o Overtime from 4,000 Hours to 600 Hours
Manufacturer of Industrial Maintenance Equipment ⁵	Material Requirements Planning	<ul style="list-style-type: none"> o Improved Inventory Accuracy from 45% to 95% o Reduced Part Shortages from 300/wk to 5/wk o Has not missed a Quarterly Production Goal for Last Three Years - Used to Meet Monthly Goals 1/3 of the Time
Manufacturer of Attachments for Caterpillar Equipment ⁶	Material Requirements Planning	<ul style="list-style-type: none"> o Inventory Accuracy from 43% to 99% o Bill of Material Accuracy from 50% to 99% o Master Schedule Performance from 63% to 95% o Delivery Performance from 55% to 95% o Shortages/Week from 150 to 0

Product/ Industry	Application	Result
Manufacturer of Aircraft Electrical Equipment ⁷	Material Requirements Planning	<ul style="list-style-type: none"> o Reduced Inventory Levels o Doubled Inventory Turns o Increased Orders Delivered on Time o Reduced Obsolete Material by 80%
Machine Tool Manufacturer ⁸	Manufacturing Resource Planning (MRP II)	<ul style="list-style-type: none"> o Inventory Reduced - 29% o Inventory Accuracy Improved from 30% to 98% o Promises Kept Improved from less than 10% to 60%
Kitchen Equipment Manufacturer ⁸	Master Scheduling	<ul style="list-style-type: none"> o Schedule Performance - 97% o Customer Service up from 89% to 96% o Finished Goods Inventory Reduced 13% o Work in Process Reduced 50% o Manufacturing Cycles Reduced 50% o Inventory Accuracy Improved from 68% to 90% <p>Note: CEO uses System to run Business</p>
Electronics ⁸	Manufacturing Resource Planning (MRP II)	<ul style="list-style-type: none"> o Labor Reduced 38% o Output Doubled o Inventory Turns went from 2.5 to 6.0 o Inventory Accuracy Better than 98%
Computer Manufacturer ⁸	Factory Data Collection/ Production Scheduling & Control	<ul style="list-style-type: none"> o Work in Process Reduced by 6% o 80% Increase in Customer Service Levels o Output Cycle Time Reduced from 35 to 12 days
75 Businesses Internal to one Conglomerate ⁹	Production Control Systems	<ul style="list-style-type: none"> o 20-25% Inventory Reduction o \$80-90 Million Productivity Improvement
		<ul style="list-style-type: none"> o Consumer Products o Light Industrial Products o Heavy Industrial Products o High Technology Products

WHAT LEVEL OF CIM WILL BE ACHIEVED?

A recent survey of the ultimate technological potential of CIM for improvement of manufacturing performance was done by a team of eight of the world's leading manufacturing research experts, from five different countries. The International Institution for Production Engineering Research (CIIP)¹⁰ asked these experts to estimate, for the metalworking manufacturing industry, the ultimate potential relative to the state of the art today. The range and average of their estimates are shown in the following table. It can be seen that they expect large improvements in manufacturing performance. While the range of estimates is large and the number is small, the averages provide a not unreasonable projection.

Forecast of Ultimate Technological Potential of CIM

ABBREVIATED QUESTIONS	ESTIMATES OF RESPONDEES	
	RANGE	AVERAGE
What do you estimate to be the ultimate percentage change, compared to today, that computer-based automation, optimization, and integration in the metalworking manufacturing industry can achieve in the following:		
Increase in manufacturing productivity?	20-200%	120%
Increase in product quality?	60-200%	140%
Decrease in lead time from design of product to initial production for sale?	30-100%	60%
Decrease in lead time from receipt of order to shipment?	30-50%	45%
Increase in utilization of capital equipment?	20-1500%	340%
Decrease in inventory of work in progress?	30-100%	75%

NOTES

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APPENDIX C
INTEGRATION IN MANUFACTURING SYSTEMS ABROAD

No country in the world yet claims to have a complete set of workable procedures for integrating the subsystems of a total manufacturing operation. The approaches currently being applied differ according to the traditions, resources, economic systems, and aims of the various countries. Nevertheless there is considerable cross-fertilization (e.g. [1,2,3]) and general optimism.

JAPAN

In Japan a concurrent scheme of two strategies has been operating since the mid-1960s. The first of these strategy-components has been a succession of government-sponsored and organized projects for the theoretical and experimental study of long-term fundamentals (Direct Numerical Control, followed by the "Methodology of Unmanned Manufacturing," and now the "Flexible Manufacturing System Complex with Laser"). Each of these projects has helped to develop a national terminology; a consensus among management, government, labor, financiers, and technicians on long-term aims and limitations; a framework for shorter-term company tactics; a general appreciation of the need for standardization and the limitations it imposes; and, finally, a sound foundation for training the CAD/CAM engineers of the future.

Parallel with their active and enthusiastic participation in these long-term projects, the Japanese companies have developed mainly pragmatic methods for integrating machine tools and transport equipment into flexible manufacturing systems (FMS). Machining information--generally in International Standards Organization (ISO) or RS tape format--is transmitted to standard CNC units in what is little more than an accelerated BTR (behind-the-tape reader) mode, and is stored there (mostly in bubble memories). The "tape" information is generated off-line, by computer-aided manual numerical control (NC) programming procedures, but these are very rarely linked organically to CAD or even to computer-aided process planning. Two integrative features, on the other hand, are very advanced indeed: one of these is the on-line scheduling of the systems (which in fact pulls the

whole act together at a very high level); the other is the advanced monitoring and failure-detection apparatus that makes "unmanned machining" possible in the second and third shifts.

Current research work at the leading Japanese universities is aimed at the development of geometric modeling and process planning systems (GEOMAP, TIPS) which hopefully will allow the numerous extant FMS plants to take a step toward CAD/CAM integration. At the same time the factories are exploiting the previous efforts invested in standardization by offering a broad spectrum of manufacturing "modules," "cells," and "islands," which can--at a relatively low systems level--be fairly easily linked and then integrated by high-level scheduling.

At this time a proposal is in an advanced stage toward acceptance for the establishment of a national program on "Manufacturing Software Engineering." This will use the "Flexible Manufacturing System Complex with Laser" hardware as a test bed for the entire life-cycle of complete CIM systems.

EUROPE

In Europe, the USSR and Germany have a long-standing tradition (dating back to the late 1920s) of concern with the scientific determination of cutting technologies. This has led in the Soviet Union and the two postwar German states to the concentration of much effort on computer-aided parts classification, process planning (determination of cutting condition, machine and tool selection, optimal trajectory determination), the establishment of machinability data banks, etc. In due course the highly developed suites of programs developed for these purposes came to be regarded as the principal mode for designing manufacturing systems for integrating CAD and CAM and for providing data to scheduling. Internal part representations were based on the process classification schemes. In recent years, however, academic research has been oriented toward increasing the weight of geometrical modeling as the integrative factor.

In the USSR there is currently a very powerful concentration of resources on the rapid implementation of FMS in a large number of plants (e.g., 16 agricultural machinery plants are now simultaneously installing such systems). The key word is standardization: the plants are all using the same computers, the same control units, and the same modular software system (MEMO), with many standardized subsystems, standard tooling, pallets, fixtures, etc. [4]. In these systems the link to CAD is rather tenuous, but the process planning systems (and their links to scheduling and manufacture) are very powerful. A rather similar approach is being adapted in Czechoslovakia.

France and Hungary have traditions in mathematical abstraction and analysis. In both countries computer-based systems have been developed and are being industrially tested for the analysis and synthesis of large, highly integrated systems. Taking as their points of departure the ideas originally proposed by Hori and Ross in the

United States and later embodied in the ICAM Definition program, researchers have sought to integrate these with the facilities of Petri-nets, relational data bases, simulation techniques, interactive graphics, etc., to offer the designer a broad palette of interrelated design tools. The initial industrial experiences have pleased users in both countries.

The United Kingdom and France have long been pioneers of numerical geometry and later of geometric modeling. (Bezier first integrated the design and manufacture of automobile bodies; Braid invented set-theoretic solid modeling.) In both these countries an intimate integration of design and manufacture has been achieved in a few selected areas (mainly automotive and aerospace). Similarly, integrated CAD/CAM systems are now appearing--e.g., for mold and die manufacture. None of these, however, has links to scheduling and management.

Finally, mention should be made of the work being conducted in a number of countries (e.g., Norway, UK, Japan, USSR) to develop multilayer, multiuser data base management systems that, it is hoped, will cover the whole area and facilitate integration. It is also hoped that these will later operate in a distributed mode through local-area networks. (The latter--and particularly their standardization--are of course themselves powerful factors for integration.)

Joint German-Norwegian CAD/CAM Integration Program

Through agreements between the West German and Norwegian governments, a joint German/Norwegian R&D program is under way called Advanced Production System (APS). It is aimed at joint development of an integrated CAD/CAM system. The prime members are Fraunhofer Institute for Production Planning and Design Engineering, Technical University of Berlin; the Laboratory for Machine Tools and Manufacturing Engineering, Technical University of Aachen, West Germany; the Foundation for Scientific and Industrial Research, Norwegian Institute of Technology, Trondheim, Norway; and the Central Institute for Industrial Research, Oslo, Norway. In addition, some 13 industrial companies in the two countries are participating in the program. These include seven system suppliers (four from Germany, three from Norway) and six system users (three from Germany, three from Norway). The program began in early 1981, and a short-term phase will run through 1985, with a long-term phase running through 1990. These phases are intended to produce a first-generation integrated system (for sale or use by the participating companies), based on integration of existing software modules, by 1985, and a second-generation integrated system, developed from scratch, by about 1990.

CONCLUSION

It is apparent (and appreciated by all the countries concerned) that none of the methods they have separately or jointly developed is as yet suitable for the fool-proof design and implementation of the "factory of the future." However, all of the methods have something to offer and have allowed spectacular progress to be made. It is widely appreciated that only the synthesis of the extant approaches, the deepening of our theoretical understanding, and, above all, the acquisition and sharing of much more practical experience can lead to a usable "science" of integration.

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GLOSSARY

Automated Manufacturing Research Facility (AMRF)

A facility at the National Bureau of Standards for examining the problems of control, data base management, and metrology associated with automated machining centers.

Computer-Aided Design (CAD)

Application of the computer to the creation, modification, or evaluation of product design.

Computer-Aided Manufacturing (CAM)

Application of the computer to the planning, control, and operation of production of a product.

Computer-Integrated Manufacturing (CIM)

Computer-integrated manufacturing (CIM) in a manufacturing enterprise occurs when:

- all the processing functions and related managerial functions are expressed in the form of data,
- these data are in a form that may be generated, transformed, used, moved, and stored by computer technology, and
- these data move freely between functions in the system throughout the life of the product,

with the objective that the enterprise as a whole have the information needed to operate at maximum effectiveness.

Concurrent Access

The ability of a data base management system to service more than one user at a time. There are degrees of concurrency; for example, a system that provides file level concurrency will permit multiple users to be connected simultaneously to the data base as a whole, but will only permit one user at a time to be using any given file within the data base, whereas a system that provides record level concurrency will even permit multiple users to be accessing the same file at any given time, but any given record can only be under the control of a single user at any time.

Data Management

The technology whereby all the data for a given enterprise are stored in a centralized repository in a computer--as opposed to the data being stored in separate, uncoordinated files. Data management implies centralized control over such aspects as organization, structural definition, privacy, and recoverability, as well as the concept that all users use this central resource instead of maintaining their own copies of the data.

Data Definition Language (DDL)

With multiple programs and users accessing a common data base, it is important that they all use a single, centralized description of the data base rather than each user describing it separately and redundantly. This centralized and common description is expressed in a Data Definition Language, usually referred to as DDL.

Data Manipulation Language (DML)

The data in a data base are accessed and manipulated by computer programs using a particular set of commands understood by the data management system. These are collectively referred to as the Data Manipulation Language or DML. Such a language may be usable on its own or may need to be embedded within some other programming language such as COBOL.

Data Model

A data base management system permits the data within a data base to be structured according to one (or possibly more) data models. Such a model defines how a user program perceives the data in the data base and usually implies certain restrictions on how the data may be accessed, interrelated, and traversed. The three most popular data models are:

Hierarchical--In this model, data relationships are restricted to a "one-to-many" structure, where any given record type can belong to only one owner (above it) in a hierarchy, but may itself own many record types (below it) in a hierarchy. It is synonymous with a "tree" structure, where a trunk can support many branches, and a branch can support many twigs, but not vice versa.

Network--In this model, data relationships may exist that reflect a "many-to-many" structure, where any given record type may be related to many other record types in a general network structure, rather than being restricted to a hierarchical tree. Thus it may be "owned" by many record types, as well as itself "own" many record types.

Relational--In this model, the different files in a data base are viewed as tabular two-dimensional matrices of "flat files," with the rows of a matrix as the records in a file and the columns as the data fields within the records. Relationships may be materialized dynamically between any two files that contain a common data field that can be used to relate the individual records in one to the individual records in the other. Also implied in this model is the ability to access and manipulate the data files (or "tables") at that level rather than on a record-at-a-time basis as is usually the case in hierarchical and network models.

Flexible Manufacturing System (FMS)

An integrated system of automated machines, equipment, and work- and tool-transport apparatus, all operating under computer control.

Integrated Computer-Aided Manufacturing Program (ICAM)

An Air Force program to improve productivity in aerospace batch manufacturing through widespread application of computer-based, fully integrated factory management and operation systems.

Integrated Program for Aerospace Vehicle Design (IPAD)

A program funded by NASA and the Navy and aimed at raising aerospace productivity through advancement of technology to integrate and manage information involved in the design and manufacturing process.

Integration

Having a data structure supporting a free flow of all data resident in the system of manufacturing to any part of the system as

needed. The data stream can, while remaining consistent, continually grow and be enriched while supporting all required functions throughout the organization and during the life of the product.

Interface

A shared boundary

Manufacturing

The Committee uses the term "manufacturing" in its broadest sense, to include all activities in the conversion of raw materials into end products. These activities range from the perception of a need for a product, through the conception, design, and development of a product, preparation for production, production of the product, marketing of the product, and, ultimately, support of the product in use.

Multilevel Schema

A multilevel schema permits data descriptions of the contents of a data base to be expressed at multiple levels of abstraction. Thus at one level, the description may show many disjoint types of records that would need to be addressed as separate units by a program using that particular level of schema. At the next higher level of schema, however, the same data may be described as one single conglomerate record that could be addressed and manipulated by a program as a single unit by referencing it through this higher level schema.

Numerical Control (NC)

Automatic control of processes by the proper interpretation of data prerecorded in symbolic form.

Product Definition Data Interface (PDDI)

An ICAM project aimed at defining needs for manufacturing data from engineering.

Schema

A description or definition of a data base in terms of its data elements and their relationships.

TABLE OF ACRONYMS

AIAG	Automotive Industry Action Group
AMRF	Automated Manufacturing Research Facility
ANSI	American National Standards Institute
CAD	Computer-aided design
CAD/CAM	Computer-aided design and computer-aided manufacturing
CAM	Computer-aided manufacturing
CASA	Computer and Automated Systems Association
CEO	Chief Executive Officer
CIM	Computer-integrated manufacturing
CIRP	International Institution for Production Engineering Research
DBMS	Data base management system
DDL	Data definition language
DML	Data manipulation language
DNC	Direct numerical control
FEDD	For Early Domestic Dissemination
FMS	Flexible manufacturing system
GM	General Motors Corporation
ICAM	Integrated Computer-Aided Manufacturing program
IGES	Initial Graphics Exchange Standard
IPAD	Integrated Program for Aerospace Vehicle Design
IPIP	IPAD information processor
ISO	International Standards Organization
MAP	Manufacturing Automation Protocol
MBB	Messerschmitt-Boelkow-Blohm
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NC	Numerical control
NRC	National Research Council
OSI	Open Systems Interconnection
PDDI	Product Definition Data Interface
ROI	Return on investment