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A Research Agenda for CIM
Information Technology

Panel on Technical Barriers to
Computer Integration of Manufacturing
Manufacturing Studies Board *and*
Cross-Disciplinary Engineering Research Committee *jointly*
Commission on Engineering and Technical Systems
National Research Council

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PANEL ON TECHNICAL BARRIERS TO COMPUTER INTEGRATION OF MANUFACTURING

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Part 1. RATIONALE AND SCOPE OF A RESEARCH AGENDA FOR CIM

OBJECTIVE

This report presents a research agenda for the information technology aspects of CIM, Computer Integrated Manufacturing. The report is intended to focus interest and guide the selection of research projects over the next five years. It is directed at researchers in academe and industry and at research-sponsoring agencies in government and industry.

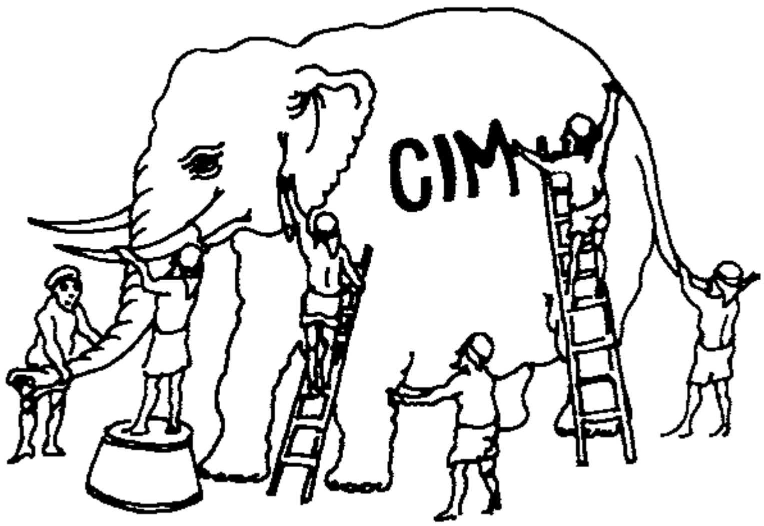
A panel of the Manufacturing Studies Board and the Cross-Disciplinary Engineering Research Committee, under the auspices of the National Research Council's Commission on Engineering and Technical Systems, wrote this report. A similar report written in 1983[1] prompted the National Science Foundation to sponsor this reconsideration of the technology and research needs five years later.

RELATED WORK

An ancient legend from India[2] deals with a group of blind men who, for the first time, encounter an elephant. Depending on whether each man touches the trunk, tusk, ear, side, leg, or tail, he proclaims that an elephant is similar to a snake, spear, leaf, wall, tree, or rope. In the modern version of this legend, there are thousands of blind people, and the elephant is CIM. (See Figure 1.)

In view of the fact that the "I" in CIM stands for "integration," it is ironic that CIM is perceived so differently by the diverse groups that relate to it: marketeers and developers of CIM products (software and hardware); purchasers of CIM products, from a broad range of industries (automobiles, pharmaceuticals, etc.); programmers who install and maintain CIM applications; intended CIM users (product design engineers, manufacturing engineers, production planners, purchasing agents, machine operators, accountants, factory managers, etc.); developers of CIM technology from industry and academe (computer scientists, industrial engineers, mechanical engineers, etc.); and perhaps even the agencies that support some of the CIM research and development. The challenge is to achieve a meaningful consensus for action.

Figure 1



This report is but one of many similar undertakings in recent years. A number of panels, workshops, and conferences have issued reports,[3] and other efforts are still under way.[4]

APPROACH

This panel's approach has been to define CIM, describe the part of CIM to be covered in this report, and then describe a taxonomy that facilitates the presentation of a research agenda. In recent years, other taxonomies have been proposed.[5] The taxonomy for this report was created by first developing a long, unordered list of potential CIM research topics gleaned from two sources:

- the collective experience of the panel, and
- a review of a number of prior reports.

The panel then reorganized the list to reduce repetition and to present the topics in three main categories: applications, enabling technologies, and synthesis. A small number of items that do not fit well under these three headings are discussed in two additional categories: long-term issues and miscellaneous. The resulting taxonomy is shown in Figure 2.

DEFINITIONS

Many of the terms that are commonly used when discussing computer-integrated manufacturing actually mean different things to different people. So that the items of the research agenda can be discussed unambiguously, the panel gives the following definitions:

Figure 2: RESEARCH AGENDA TAXONOMY

- CIM Applications
  - Manufacturing resource management
  - Process operation
  - Process planning
  - Product and process design
- CIM Enabling Technologies
  - Modeling
  - Computing resources and resource management systems
- CIM Synthesis
  - Overall architecture
  - Requirements analysis
  - Human role
- Long-Term Issues
- Miscellaneous

Manufacturing

Manufacturing is the collection of physical and intellectual activities associated with designing and making tangible, movable items of value, either by hand or through the use of machinery.

Interfaces

Interfaces are linkages among independent systems, each capable of doing something useful.

Integration

Integration is the combination of two or more independent systems in such a way that the composite system does more than the initial collection. The scope of integration varies from simple interfaces to complex redesign of entire systems.

Most systems are already integrated, although the effectiveness of this integration may be limited. For example, industrial enterprises are integrated; manufacturing is integrated. In this context, promoting integration means improving effectiveness. Qualitative changes occur in the overall system as the effectiveness passes certain thresholds.

Computer Integration

Computer integration refers to situations in which computing is the agent of integration. The principal forms of computer integration are:

- common data bases and communications links (i.e., sharing data),
- common system and application programming interfaces (i.e., sharing executable programs), and
- common user interfaces (i.e., having similar screens and keystrokes).

Effective integration usually requires significant attention to the overall system architecture. The two main technical issues are how computer integration may be facilitated and how it can be applied.

Computer-Integrated Manufacturing

Computer-integrated manufacturing is manufacturing in which computers serve as an important agent of integration. The computing hardware and software involved are termed CIM systems.

CIM SYSTEM STRUCTURE

Outputs

The use of a CIM system results in two possible outputs:

- Products to be sold to customers. The products may be either physical (e.g., an automobile) or informational (e.g., a design for an automobile). The customers may be either outside or inside the enterprise operating the CIM system.
- Production systems to be used for manufacturing. These are tools for making the products rather than the products themselves. Again, they may be physical (e.g., a manufacturing line) or informational (e.g., part of another CIM system).

Logical Components

There are many ways to view the structure of any CIM system that provides such outputs. One way is to start with the highest level of application and progressively decompose the system into successive levels of function. A recursive similarity is displayed as the layers are peeled away. This process should not be confused with the agenda taxonomy of Figure 1.

An application is the highest-level useful function performed by a CIM system. For example, job-shop scheduling might be a CIM application. Any application has two major components, modeling and subordinate applications.

The first component, modeling, deals with the top-down view of the specific application domain. It can be subdivided into four major parts:

- representing the application states and transitions among them;
- predicting transitions;
- facilitating decisions among possible transitions (these decisions may be interactive or automatic, algorithmic or heuristic, etc.); and
- controlling the transitions by closed-loop feedback, with people removed from many of the mundane, error-prone, or real-time-critical decision-making roles.

For example, the application state for a shop-floor control system would include the set of jobs in process; their priorities, deadlines, and degrees of completion; the material flow routes; the set of machines and queues; which jobs the queues currently contain, etc. Transitions would include job release, machine cycle completion, installation of new machines, changes in job priority, etc. Predicting transitions would include forecasting machine utilization or job completion times. Decisions would include selecting jobs from each queue, scheduling machine maintenance, etc. Controlling transitions would include automatically raising the priority of a job as its deadline approaches, sounding an alarm when a queue overflows, etc.

The second component of an application is the set of subordinate applications. For example, a job-shop scheduler might include a materials resource planner and a machine tool utilization analyzer as subordinate applications.

CIM applications that deal solely with providing or managing computing resources include operating systems, data base management systems, central processing units, data bases, input/output, communications networks, and user interfaces. As long as these functions are essentially independent of manufacturing, their inner operation is outside the scope of CIM.

Because applications are built on top of other applications, CIM systems tend to be highly layered. At the lower levels, the system modeling technology may be application-independent. Progressively higher layers introduce objects that tailor this generality to specific domains.

BOUNDING THE RESEARCH AGENDA

In its broadest definition, CIM is a very complex subject for a research agenda. This report, as noted at the outset, focuses on the part of CIM research with the highest potential leverage: the handling of information.

The major functions of a business enterprise are manufacturing and marketing. Although this report has defined manufacturing to include designing as well as making products, these functions historically have been split apart, relating to the distinction between white-collar and blue-collar labor. Similarly, production control and process operation have been divided by the distinction between indirect labor (including management) and direct labor.

In both of these cases, the boundaries have evolved for reasons that are expedient rather than intrinsic. The essence of integration requires that it cross such artificial boundaries. It is usually unwise to design products independently of the plants that will produce them, or to schedule process operations independently of product characteristics. The research proposed in this report is aimed at integrating those functions.

Similarly, manufacturing and marketing are interrelated. Products should not be manufactured unless they can be sold, or sold unless they can be manufactured. Although this report excludes marketing, some research in this area is desirable.

Since the time of Henry Ford, material transport systems have been important integrating elements in manufacturing. This report, however, limits the CIM research agenda to the computational aspects of manufacturing; material transport systems are considered only to the extent that they represent subsystems for which computing has a significant benefit.

The impediments to rapid and effective implementation of CIM span a broad range of issues:

- management (organizational, governmental, sociological)
- finance (justification, measurement)
- personnel (human factors, human resources, education, training)
- technology transfer
- technology availability

Experience indicates that all of these issues are important. To conform to the charter of the panel, however, this report focuses on the availability of technology for CIM.

THE NEED FOR A CIM RESEARCH AGENDA

The rationale for government-sponsored research in manufacturing has two elements:

- Research will provide new technology; this technology will improve manufacturing; and this improvement will increase the nation's industrial effectiveness.
- Individual companies cannot be expected to bear the full costs of research whose benefit is likely to spread beyond company boundaries.

Research on CIM is part of manufacturing research. The general rationale for research specifically in CIM has three elements:

- The potential benefit from integrating manufacturing subsystems is large.
- Implementing CIM is proving to be much harder than expected.

- The gap between expectation and reality is due partly to technical problems that research can solve.

Occasionally raised in opposition to CIM research are two arguments:

- No essential differences exist between a CIM system and other large, dynamic, heterogeneous computer applications, such as airline reservation systems. If gaps exist in the computing technology needed for CIM they are small, and existing research aimed at broader needs will automatically address them.
- Integration is an evolutionary step that occurs progressively as any complex human-made system grows. Integration occurs naturally in response to socioeconomic pressures, and innovative technology is rarely a limiting factor.

The first view holds that CIM research is unnecessary; the second that it is futile. The response to the first is that a CIM system is different from other large systems in many quantitative ways: The variety of system users is greater; the variety of domains is greater (from automobiles to pharmaceuticals); the variety of nonhomogeneous computing systems is greater; the number and variety of parameters may be larger; the system may change more frequently; the system is more sensitive to capricious human decisions; and the system is sensitive to a greater variety of unpredictable, real-world events. In addition to these differences are similarities, but they consistently relate to the most difficult classes of system complexities: Systems may produce other systems; data bandwidth and storage requirements are very high; many of the applications are combinatorial and therefore mathematically hard.

The response to the second view is that evolution is an intrinsically inefficient way to reach a goal, and it is unlikely to achieve the same results as a planned effort. An integrated view of manufacturing should help define and accelerate the changes in the system components and in the framework that is needed to allow their integration. The benefits of even short lead times in implementing CIM are so large that any useful results from CIM research are likely to more than repay the investment. Additionally, funding research in CIM is likely to foster related research in contiguous domains of manufacturing.

MAJOR THEMES

The research agenda in this report is subdivided into many individual topics for tractability. Underlying the details of these individual projects are two significant common themes.

The first theme is that the manufacturing environment shapes CIM. This environment is characterized by the following attributes:

- Time is a major constraint on the use of data at all levels of manufacturing. The meaning of real time may vary from microseconds to days, depending on the application, but in each case it establishes a threshold for application feasibility. Therefore, techniques that accelerate data acquisition, storage, retrieval, and processing have large potential impact.

- Change is a major factor in manufacturing. Changes affect products, processes, computing technology, market demand, competition, etc. The utility of CIM systems depends on their long-term ability to accommodate such changes. Therefore, techniques that provide better ways to structure CIM systems have large potential impact.
- Complexity is a major attribute of manufacturing. The dimensions of this complexity include the flows of materials and data, the structure of products and processes, the diversity of vendors and suppliers of materials and equipment, formal and informal interactions among personnel, and diversity across industry types and applications. The utility of CIM systems, however, depends on their having generic reusable components. Therefore, techniques that provide better means of classifying requirements and building system components have large potential impact.

The second common theme is that much of manufacturing is based on experience rather than on systematized scientific knowledge. To facilitate CIM, therefore, a focus of research should be the identification and formal characterization of manufacturing objects at progressively higher levels. This approach will permit future CIM systems to deal with progressively higher levels of abstraction.

The second theme is addressed in both a top-down and a bottom-up manner. The top-down direction deals with overall CIM architecture and its progressive decomposition, stressing the generic role of modeling and information flow. The bottom-up direction emphasizes the common tools for building advanced CIM. Among these tools are object-oriented systems, artificial intelligence, symbolic mathematics, control theory, and the use of hybrid systems that combine knowledge-based techniques with other algorithmic and heuristic components.

ELEMENTS IN THE RESEARCH AGENDA

The remainder of this report contains the research agenda. Each item in the agenda has three components:

- a discussion of the issues that the item encompasses,
- a list of specific subjects for research (or in some cases discussion of broader research areas), and
- a rating of each specific subject.

The ratings employ the letters L (low), M (medium), and H (high), and each is in the form of three letters--e.g., H, H, M. The first letter refers to the level of impact that the research would have if it were successful. The second is a measure of the effort needed to do the research; generally speaking, low effort takes less than three years and $1 million, while high effort takes seven years and $15 million. The third letter is a measure of the intellectual content and technical risk of the research.

The panel recognized that such ratings are inevitably subjective and that other people would come up with a different set of ratings. The effort, direction, and success of individual research projects are hard to predict. Recognizing the interdependence of research projects makes prediction even harder, and assessing exactly what problem a given project is attempting to solve entails considerable ambiguity. Further, the impact in terms of real CIM applications depends on management, financial, and human issues that researchers are largely without power to affect. In spite of these shortcomings, the panel decided to add the ratings to the research topics to give readers some basis for establishing priorities among the many projects proposed.

Projects with high impact and low risk, for example, are likely to be undertaken by industry, irrespective of government funding decisions. Conversely, projects with low cost and high risk are often attractive thesis topics in academe. Projects in other categories are less likely to be undertaken, without added stimulus from government funding. Some possible strategies for funding agencies might be:

- commitment to the long term: High impact, High effort, High risk
- investment for the future: High impact, Medium effort, Low risk
- exploratory research: Medium impact, Medium effort, High risk
- best bets for quick results: Medium impact, Low effort, Low risk

In general, high-risk projects are better suited to academe. High-cost projects require a commitment to multidisciplinary cooperation, progressively crossing the boundaries of academic departments and institutions. Engineering research centers or their equivalents are appropriate. Very high-cost projects require industrial involvement, possibly in the form of consortia.

The uncertainties in the ratings suggest an overall strategy that combines several types of projects. It is worth reiterating that all of the topics proposed in this report would contribute to the ability to achieve computer integration of manufacturing, and the ratings are intended only as rough guidelines.

Part 2: THE RESEARCH AGENDA

CIM APPLICATIONS

Manufacturing Resource Management: Planning, Setup, Scheduling, Control

The principal components of the problem of resource management are a set of resources, a set of physical and operational resource constraints, a set of demands to be met, and a measure (or set of measures) of the goodness of any specific resource allocation. The goodness measure often involves conflicting objectives, such as minimum work in progress, maximum throughput, and maximum capital utilization. Customarily, it is assumed that the set of demands has already been mapped by a preliminary process planning step into a set of sequences of resource requirements.

Although resource management is inherently dynamic, it is often abstracted into a static problem of allocating resources to optimize the performance measure while meeting the constraints and demands. Because the system is likely to have time lags or dynamic effects, one has the more difficult problem of choosing an allocation trajectory that over time approaches the static optimum in a stable manner. The dynamic problem is to provide these solutions in a manner that can adapt to real-time changes in the constraints, the demands, the resource set, and possibly even the performance measure. An additional problem is the statistical inference of how many parts to start producing in order to compensate for anticipated probabilistic yield losses.

For CIM, the resources include materials, machines (process and transport), people (including maintenance), information, and money. The physical constraints include availability, capacity, and setup time for various resources. The operational constraints include response times for detecting and adapting to changes. The problem then is to plan production before demand is precisely known, to schedule production when demand is known, and to adapt these schedules in response to real-time changes, such as in manufacturing demand or machine availability.

Using existing production information control systems to operate specific manufacturing lines is CIM, but it is not research. CIM research is needed in the following areas:

	Impact	Effort	Risk
• Methods for modeling a wide class of resource problems, especially methods based on knowledge-based systems, object-oriented systems, and Petri nets; methods that are sufficiently fast and efficient that resource problems are tractable while plants are being designed and built, as well as being operated; methods for verifying the correctness of models, based in part on comparisons of predicted and measured performance.	H	H	M
• Modeling methods that allow easy interchangeability of models and the real objects they represent; application of such methods to allow smooth transition between simulated production and real production.	H	M	L
• Planning and scheduling algorithms and heuristics, especially those based on operations research, control theory, artificial intelligence (AI) inferences,[7] and simulated annealing.[8]	H	H	H
• Methods for coupling process planning with resource allocation so that the two decisions can be reached concurrently.	M	M	L
• Statistical methods for inferring how many parts to start producing in order to meet the demand for good parts when yield rates are low and highly uncertain, especially in production facilities that manufacture a variety of advanced semiconductor devices.	L	L	M
• Methods for analyzing the sensitivity of schedules to changes in input constraints and demands; resulting formal definitions and measures of system flexibility; resulting methods for planning optimal structures for flexible manufacturing systems, down to the level of layouts of tools and transport systems.	H	M	H

RESEARCH AGENDA TAXONOMY

CIM Applications
- Manufacturing resource management
- Process operation
- Process planning
- Product and process design

CIM Enabling Technologies
- Modeling
- Computing resources and resource management systems

CIM Synthesis
- Overall architecture
- Requirements analysis
- Human role

Long-term Issues

Miscellaneous

	Impact	Effort	Risk
• Methods that use cost to approximate more complex resource constraints; in particular, methods that use marginal costs imposed by delay in order to optimize schedules; methods for estimating costs in complex systems.	H	H	H
• Methods that automatically trade off model complexity and decision accuracy against computational speed; application of these methods to identify bottlenecks in advance and to use feed-forward scheduling to avoid starvation or clear it quickly when it occurs.	H	H	H
• Computational techniques that speed up all these systems to increase their capacity to respond to real-time changes, including new computer architectures, e.g., a Petri net computer, which may provide significantly greater computational speed for these problems.	M	M	L
• Methods that rapidly diagnose systemic resource management problems, based on models and actual performance, and recommend changes to correct these problems and support queries that permit the models and recommendations to be validated, i.e., a diagnostic "factory doctor."	H	M	L

It is important that the approaches to research in these areas not be restricted to idealized toy domains or to domains that are excessively narrow.

Process Operation: Analysis, Optimization, Control, and Quality Assurance

Process operation in general deals with a collection of equipment, each piece of which can perform chemical and physical process steps, each in turn producing physical changes in products or equipment. The actual changes should correspond to specifications of desired changes. Each process step is governed by a set of controllable parameters, the state of the incoming products, and the dynamics of the process equipment itself. Each process step may be deterministic or stochastic.

Information about the actual effect of each process step may be provided by in situ process monitors or by downstream product measurements, based on either statistical sampling or exhaustive study. The information may have both systematic and random components; in addition to variations in material and process parameters, the randomness may be due to imperfections in the measurement systems.

The process analysis problem is to understand how each process really works. The understanding of equipment and process can then be represented by models, often in the form of equations that approximate the observed phenomena.

The process optimization problem is to determine the operating states and sequences for the collection of process steps. Usually the problem is subdivided into optimization of the steps individually.

The process control problem is to design and implement procedures that use feedback, especially from in situ monitors, to modify the controllable parameters. As with any servo system, process control reduces the sensitivity to uncertainty or error in the process models.

The quality assurance problem is to detect deviations quickly when the actual changes produced by a collection of processes differ unacceptably from the desired ones, and then to identify one or more process steps whose behavior is the cause.

Using existing monitors and control techniques is an important part of building a useful CIM system, but it is not research. CIM research is needed in the following areas:

	Impact	Effort	Risk
• Methods that allow sets of processes to be analyzed, optimized, and controlled collectively rather than as individual steps.	H	H	L
• Generic methods for modeling a broad range of individual processes, possibly through use of knowledge-based techniques; modeling methods that encompass discrete statistical phenomena, continuous phenomena, and macroscopic geometry, for applications such as processes that involve phase changes.	M	H	M
• Recognizing that full interchangeability of automated machine tools and equipment cannot be achieved, methods for dealing with near interchangeability, based on characterization, sensing, and software; resulting application to modular flexible manufacturing lines.	M	L	L
• Methods for improving model efficiency to allow real-time simulation of processes; methods that allow complex models to be automatically simplified or aggregated to facilitate faster analysis of specific properties.	H	M	H

RESEARCH AGENDA TAXONOMY

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- Modeling
- Computing resources and resource management systems

CIM Synthesis
- Overall architecture
- Requirements analysis
- Human role

Long-term Issues

Miscellaneous

	Impact	Effort	Risk
• Methods for coupling process planning with process operation so that the two may be accomplished concurrently; a demonstration that such coupling is feasible for at least one application, such as robotic assembly.	M	L	L
• Generic methods for diagnostic backtracking from detected defects to faulty process steps, especially those involving artificial intelligence inference; diagnostic methods for initiating preventive maintenance; forecasting methods to predict maintenance needs.	M	M	M
• Families of new sensors, especially with built-in processors, for a variety of processes, such as large-area nondestructive assessment of surface quality (metal, silicon, paint).	M	M	M
• Generic methods of synthesizing information from complementary sensor systems (sensor fusion) and dealing with incomplete, inconsistent, and contradictory information.	M	H	M
• New architectures for highly programmable multiprocessor hardware and operating systems that can be applied to the control of a variety of processes, including metal cutting, photolithography, molding, casting, and robotic assembly and test; assessment of such controllers in complex tightly coupled control applications.	M	H	L

Process Planning

The general problem in process planning is to derive a set of sequences of resource requirements from models of the product and the available processes and the constraints that interrelate them. In the first stage, the input is typically a description of the initial and final states of products and materials, the set of equipment and the corresponding processes, the process constraints, and the personnel and equipment availability; the output is a feasible sequence of tools and operations that would transform the initial materials into the desired final state. In the second stage, the input is a set of feasible process plans and a measure for choosing among them; the output is a particular plan.

A tenet of CIM is that the same models of products and processes should be used for both process planning and process operation. Similarly, the same models of equipment and resource constraints should be used for both process planning and resource management.

Computer-aided process planning (CAPP) is often divided into two phases. In the first, the product design is mapped into a set of manufacturable features. This may be an enforced discipline at product design time, or it may involve an independent step of feature recognition. In numerically controlled (NC) machining the features might include holes and milled surfaces, while for computer chip processing the features might include regions, junctions, and profiles. In the second phase, one or more feasible manufacturing sequences are derived that are consistent with process constraints. These constraints often take the form of partial time orderings inherent in the processes available to create the features. The resulting process plan is rarely checked for consistency with the resource constraints, which are subject to change.

In discrete part manufacturing, for example, many efforts have been made to develop so-called Group Technology classification codes, based on part shape features. These codes have then been used as the basis for generating process plans, either ab initio or by varying existing plans for other parts with similar codes.

Process plans are usually judged by simplistic criteria, such as the total number or cost of all the process steps. Even so, the combinatorial nature of process planning problems makes them mathematically hard, precluding algorithmic optimal solutions except for trivial products. Heuristics are the norm, and their absolute performance is usually not assessed.

CAPP is easiest for products that are essentially two-dimensional. As the scope and speed of CAPP improves, it will increasingly be integrated into the design process, facilitating design for produceability.

Because CAPP is mathematically hard, specific application development is still sufficiently new that it qualifies as CIM research. In addition, CIM research is needed in the following areas:

	Impact	Effort	Risk
• Process planning techniques that work for specific important domains, such as NC machining or semiconductor device fabrication, especially using knowledge-based approaches; underlying methods that (a) represent manufacturable features, especially with mathematical rigor; (b) allow identification of manufacturable features at design time; and (c) apply pattern recognition techniques for automatically identifying features in an existing design, including both algorithms and heuristics.	H	H	M

RESEARCH AGENDA TAXONOMY

CIM Applications
- Manufacturing resource management
- Process operation
- <u>Process planning</u>
- <u>Product and process design</u>

CIM Enabling Technologies
- Modeling
- Computing resources and resource management systems

CIM Synthesis
- Overall architecture
- Requirements analysis
- Human role

Long-term Issues

Miscellaneous

	Impact	Effort	Risk
• Process planning techniques that, in addition to generating tool and operation sequences, also generate lower-level procedures for setting up tools, controlling them, and advising operators.	H	M	L
• Methods for coupling process planning with resource allocation and process operation so that these activities can be accomplished concurrently, especially methods that defer final selection among process plans as long as possible.	M	M	L

The approaches to research in these areas may be based on idealized toy domains, but it is important that they not be technical dead ends with respect to realistic complex parts and machines.

Product and Process Design

The general problem with product and process designs is to provide a hybrid environment in which they can be created, analyzed, and modified easily. Design starts with vague concepts about ultimate function. These ideas are refined on the basis of concurrent analyses of product and process, including function, appearance, reliability, manufacturability, complexity, cost, lead time, repairability, field support, etc. The final output is a set of specifications that describe the design in great detail; mechanical drawings are often part of the output specifications.

Design is not smooth and progressive; usually it involves the abandonment of avenues after their in-depth analysis. If these restarts are overlooked, the overall pattern proceeds from concept to functional features to manufacturable features. Process planning may be viewed either as a late stage of design or an early stage of manufacturing.

Originally, the use of computers for design meant computer-aided design (CAD) systems that emphasize interactive graphics with a human designer initiating each transaction. Recent years have seen increasing emphasis on the underlying models of products and processes, based on the realization that to help synthesize designs an expanding set of programs needs access to the designs. A tenet of CIM is that the same models of products and processes that are created and utilized at design time are also used for process planning, process operation, and resource management.

Many CAD systems are commercially available. Historically, these systems focused on individual productivity, but the emphasis is shifting to simultaneous engineering design involving groups of people. The need to integrate these systems has led to efforts to standardize data structures.[9] Meanwhile, CAD vendors have been differentiating their products by adding new functions. It is not clear whether the standards efforts are keeping pace; perhaps standards can never be more than lowest common denominators. In any case, developing standards that link

CAD data structures is important to CIM, but it is not research. CIM research is needed in the following areas:

	Impact	Effort	Risk
• Data structures for describing products in terms of conceptual design, functional features, dimensions and tolerances, manufacturable features, and so forth; methods that allow such structures to be interfaced with other CIM components, such as knowledge-based systems.	H	M	L
• Generic approaches to modeling products, equipment, process states, and dynamic behavior, bridging three fundamental domains: discrete statistical phenomena (e.g., atoms, ions, molecules), continuous systems phenomena (e.g., differential equations for diffusion, wave propagation), and macroscopic geometry.	H	H	H
• Methods for coupling design with process operation, so that process control programs can be derived from designs and vice versa.	H	M	M
• Exploration of canonical decompositions of three-dimensional shapes, including algorithms and heuristic feature recognition approaches; algorithms for automatic synthesis of finite element meshes based on solid shape, differential equation, and boundary conditions; application of these algorithms to the automated analysis of stress.	M	M	M
• Advances in computational geometry, especially those that ensure the precision of geometric models and operations.	H	M	H
• Methods that allow complex models to be automatically simplified or aggregated to facilitate faster analysis of specific properties.	M	M	L

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Long-term Issues

Miscellaneous

	Impact	Effort	Risk
• Development and assessment of design rules, including function, appearance, reliability, manufacturability, cost, complexity, lead time, repairability, field support, etc.; related development of design assessment tools; validation of these approaches with case studies.	H	H	M
• Special computer architectures and algorithms that accelerate design analysis and synthesis, especially those involving parallelism.	H	H	M

CIM ENABLING TECHNOLOGIES

Modeling

The previous section described the important application domains of manufacturing resource management, process operation, process planning, and product and process design. Common to these domains is an underlying modeling technology that includes elements of representation, prediction, decision, and control.

When modeling is applied to specific domains, the level of sophistication depends on that domain and on the industry type. For many years, for instance, continuous processes like petroleum refining have been run by systems that are more highly integrated than those in discrete parts manufacturing. They include the representation of plants and processes, the prediction of their behavior, the selection among process recipes, and the use of control theory for closed-loop servo control.

The general problem of representation deals with the immense variety of objects that need to be modeled for manufacturing. An increasing number of hybrid modeling techniques are becoming available, especially those involving object-oriented systems, knowledge-based systems, geometric modeling, ordinary and partial differential equations, symbolic mathematics, and Petri nets.

CIM research is needed in the following areas of representation:

	Impact	Effort	Risk
• Higher layers that progressively tailor these general hybrid tools by defining manufacturing objects for specific real domains of moderate complexity; resulting assessment of the adequacy of the tools and objects for modeling systems of realistic levels of complexity.	H	H	L
• Improved methods for human interaction with complex models, probably based on graphics, to facilitate their creation, examination, and modification.	H	H	H
• Interactive and autonomous methods for verifying the correctness of models.	H	M	M

The general problem of prediction deals with the derivation of useful insight from complex models. Given a representation of a CIM system, it should be possible to predict how it will behave. Without prediction, representation becomes an end in itself, from which no practical benefit can be gained.

Because predictions at the level of individual events would lack statistical significance, some form of aggregation is needed to allow predictions to serve as tests of the validity and utility of models. Even then, it may be difficult to establish bounds of significance.

CIM research is needed in the following areas of prediction:

	Impact	Effort	Risk
• Methods for representing aggregation and for automatically deriving aggregate classes from detailed models.	M	M	H
• Methods for deriving predictions from models, including analytical techniques of operations research and control theory, AI techniques of pattern recognition and inference, and hybrid techniques.	H	H	M
• Methods for assessing the statistical significance of predictions, especially those derived from detailed models; resulting methods for determining which model components are critical.	H	M	M

The problem of decision is to assist CIM users in choosing among possible actions. The decision is difficult if the number of actions is large or if the assessment of individual actions is costly, inaccurate, or ambiguous. Dealing with uncertainty and risk adds further complications.

CIM research is needed in the following area of decision:

	Impact	Effort	Risk
• Methods for representing decision objects, e.g., states, actions, utilities, prior and posterior probabilities, samples, costs, and decisions; methods for mapping these objects to manufacturing objects; development of relevant heuristics and algorithms; exploratory assessment of the merit of these techniques in specific domains.	M	H	M

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CIM Synthesis
- Overall architecture
- Requirements analysis
- Human role

Long-term Issues

Miscellaneous

At the level of individual processes, decisions are so frequent that a human cannot be an effective part of the feedback and control loop. As computing capabilities continue to improve, the same effect is being seen at the level of manufacturing lines and plants.

CIM research is needed in the following areas of control:

	Impact	Effort	Risk
• Application of control theory, especially nonlinear and adaptive control, to manufacturing processes, cells, lines, and plants.	M	M	L
• Exploration of the role of symbolic mathematics processing in process analysis, control, and optimization.	M	L	H

Computing Resources and Resource Management Systems

Among all the applications of general-purpose computers, CIM is still a small fraction. One measure of technical progress in general-purpose computing is that over the past 30 years the real price of computing systems has dropped 20 to 25 percent per year.[10] These advances automatically benefit CIM, and they can be expected to continue.

In many instances, CIM would benefit if systems developed for general purposes were tailored to manufacturing needs. For example, some manufacturing plants may have unusually stringent requirements regarding dirt, audio or radio noise, or downtime. Additionally, most of manufacturing has critical real-time requirements regarding timeliness of data, which in turn depends on communication bandwidth, latency for data retrieval, and processing speed.

In those cases in which general purpose systems may be deficient for CIM, it is important to identify and develop the enhancements that are needed. The alternative of circumventing CIM architectures to compensate for the deficiencies is expedient but short-sighted.

CIM research is needed in the following areas:

	Impact	Effort	Risk
• Methods for characterizing the data storage and communications requirements for real-time distributed applications.	H	M	L
• Methods for modeling, analyzing, simulating, and managing large heterogeneous communications networks; performance measures for assessing networks; systems to facilitate the design, operation, tuning, and easy modification of networks, based on these methods and measures.	H	M	L

	Impact	Effort	Risk
• Methods for including executable programs and rules within distributed data bases without sacrificing access speed; methods that ensure data consistency and validation; generic data base techniques for efficient storage of voluminous time-dependent data, for automatic data reduction based in part on pattern recognition and induction, and for real-time access; specifically, methods for establishing limited data entry and automatic data reduction, based on constrained data storage and communications capabilities.	M	L	L
• Methods for automatically deriving tests to validate communications protocols, based on formal descriptions of the protocols and the networks in which they will operate.	M	M	L

Interest has been growing in the use of knowledge-based systems and artificial intelligence languages like Lisp and Prolog for manufacturing applications. Progress in such applications will require enhancements in dealing with concurrency and real time.

CIM research is needed in the following areas:

	Impact	Effort	Risk
• Extension of concurrent multiuser access techniques from data base systems to knowledge-based systems.	H	M	H
• Extension of knowledge-based systems and AI languages to support parallel processes, real-time event handling, and elimination of uncontrollable garbage collection latency.	H	M	H

CIM systems to date have been based primarily on conventional general-purpose computers. The fact that special-purpose graphics processors are inside modern CAD workstations, however, is an indication that the potential role of special-purpose processors is growing rapidly.

A way is needed to focus this potential on CIM. CIM research is needed in the following areas:

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CIM Applications	<u>CIM Synthesis</u>
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	Long-term Issues
CIM Enabling Technologies	
Modeling	Miscellaneous
<u>Computing resources and resource management systems</u>	

	Impact	Effort	Risk
• Design and application of special computer architectures, especially highly parallel processors and signal processors, for geometry, communications, control, discrete event simulation, and pattern recognition.	H	M	H
• Exploration of the potential of self-learning systems within CIM, especially neural nets.	M	M	M

CIM SYNTHESIS

Overall Architecture

Overall architecture for CIM deals with the basic question of how a large CIM system can be designed, developed, and modified in an orderly fashion. Ease of modification deserves special emphasis because installed CIM systems usually have a long life, during which products, processes, computing technology, and applications often change considerably.

The highest-level architectural issue is the development of a CIM reference model that offers a formal means of characterizing CIM systems in general. Such a characterization would automatically permit this or any research agenda to be checked for completeness. Subsequent steps involve exploration of how the overall system can be naturally partitioned.

In order to define and develop a CIM architecture, CIM research is needed in the following areas:[11]

	Impact	Effort	Risk
• A reference model for CIM, i.e., a formal description of the highest-level CIM system, with a progressive decomposition of its component subsystems. An example of such a reference model in a different domain would be the International Standards Organization's seven-level model of communications.	H	M	L
• Identification of the major classes of end users of CIM systems and the views of the data that each requires from the overall system. Three such classes, for example, might be operators, maintenance workers, and product designers.	M	M	L
• An architecture for the CIM run time environment, i.e., the system actually used for operational control, sufficiently open to be compatible with vendor and application heterogeneity, probably table driven, and possibly based on data flow.	H	H	L

	Impact	Effort	Risk
• An architecture for the CIM build time environment, i.e., the system used to create and modify the run time system, including the objects and methods that provide the software development facilities for building, maintaining, and modifying run time systems.	H	H	L
• Exploration of analogies between material flow and data flow, including such concepts as "bill of data," data requirements planning, and just-in-time data.	H	L	H
• Methods of building shells around arbitrary existing systems, such as commercially available CAD or production information control systems, to encapsulate them within object-oriented interfaces that are compatible with a common distributed architecture.	H	M	L

Requirements Analysis

Some CIM system requirements cross the boundaries of the applications enumerated earlier. These requirements deal with the network topology, storage, and real-time latency and bandwidth.

Common practice at the earliest stages of designing CIM systems is to make almost arbitrary decisions regarding hierarchical levels, the amount of central processing unit power and storage at each node, interconnection topology, the bandwidth of communication links, and the partitioning of tasks among processors. These decisions, in turn, have an overwhelming effect on the function, performance, and cost of the resulting operations.

Few engineering tools are available to help quantify the requirements at any level. In order to help identify and quantify information requirements in various domains of manufacturing, CIM research is needed in the following areas:

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<u>CIM Synthesis</u>
- <u>Overall architecture</u>
- <u>Requirements analysis</u>
- <u>Human role</u>

Long-term Issues

Miscellaneous

	Impact	Effort	Risk
• Methods of modeling the storage, flow, and processing of information in CIM systems; simulation and analysis based on these models to predict real-time performance.	M	M	M
• "Task level" methods for automating the design of plants by modeling CIM systems in terms of their material and information objectives rather than their detailed structure; methods of deriving topology, storage, and real-time requirements from such models.	M	M	H

Human Role

Growing evidence and the strong personal opinions of CIM practitioners indicate that changes in traditional management and labor practices, organizational structures, financial systems, and decision-making criteria are needed to make highly integrated manufacturing enterprises operate effectively. Such topics fall more in the area of management than in conventional technology; they have an overwhelming impact on the ability of an enterprise to function efficiently and respond rapidly to external changes in markets and consumer demands.

People and organizations are interwoven with the integration process. Higher levels of CIM often require extensive training programs and a change in the traditional culture in the factory so that employees at all levels of the organization are viewed as a resource. Organizational structure, quality of work, and work assignments are all relevant.

Traditional financial methods for justifying investments and allocating costs to products are not appropriate for CIM, since the benefits cross parochial boundaries. Risk aversion in traditional methods seriously impairs the likelihood of making investments that are critically important to long-term success.

Current justification procedures relying on return-on-investment calculations tend to emphasize easily quantified savings in labor, materials, or energy and usually look only at arbitrarily truncated periods of time. The difficulty lies in the disparity between the apparent ease of quantifying costs and the difficulty of quantifying an unusually broad range of benefits. Such benefits include flexibility, cycle time, product and process quality, assets utilization, and customer satisfaction.

Product costing methods that rely on allocating overhead on a base of direct labor become meaningless as CIM blurs the distinction between direct and indirect labor. It is also apparent that increasing full employment policies and the high value of systems and fixed assets make fixed-to-variable-cost ratios very high. Product costing, cost of goods sold, and inventory value will increasingly need to be based on allocating overhead to material and to value-add time.

Although no specific research projects are proposed here, this set of broad managerial issues indicates rich opportunities for highly innovative research in human behavior, organizational development, and manufacturing economics.

Another aspect of the human role in CIM deals with user interfaces to CIM systems. CIM involves widely diverse users who in turn require specialized user interfaces. In recent years, computer science has made strides in providing programming tools for building user interfaces. Most existing CIM applications have ignored these tools in favor of ad hoc unique user interfaces. The problem is to close this gulf.

CIM research is needed in the following areas:

	Impact	Effort	Risk
• Models of individual user interface ergonomics, i.e., their physiology and psychology with respect to intellectual and mechanical tasks that are characteristic of manufacturing; models of user group interactions; ergonomic testing of users to validate these models.	M	M	M
• Improved user interfaces for explanation and inference, including the use of natural language and speech synthesis and recognition.	M	M	H

LONG-TERM ISSUES

Increasing success in commercial application of CIM masks a disturbing lack of basic theoretical underpinnings for the whole field. The preceding list of CIM research topics addresses none of these fundamental long-term issues. Instead, it identifies specific topics that appear likely to yield continuous incremental progress.

For the long-term issues, on the other hand, insight on how to start is currently lacking. These long-term issues are high in risk; they have deep intellectual content, the probability of success is low, and even if success were achieved, the potential impact is completely unknown. Innovative ideas are needed in the following areas:

- A theory of design, especially conceptual creative design.
- A theory of manufacturing; exploration of analogies with continuous systems behavior, such as diffusion, wave propagation,

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thermodynamic systems; exploration of the relevance of information theory.

- A theory of systems integration.
- A theory of organizational behavior.

MISCELLANEOUS

Although mechanical engineering is generally outside the scope of this report, isolated instances exist in which advances in mechanisms could have far-reaching effects on the applicability of CIM. Examples of research topics might include methods that allow high-speed navigation and traffic control of mobile robots in factories.

Educational systems are also outside the scope of this report. The lack of a CIM skill base, however, is a sufficient impediment to rapid application to warrant some research on CIM education.

In this context it is worth noting that during the early period of robot technology development, from 1970 to 1980, the existence first of the Scheinman Arm and later of the Puma served to integrate academic researchers. In the same spirit, if the academic community were to define a prototypical CIM vehicle, consisting of some combination of software and hardware, this consensus might accelerate the development of a cohesive approach to CIM research.

CONCLUSION

This report has presented a large number of topics for research on CIM. Underlying them are two common themes:

- The manufacturing environment is characterized by time constraints, continual change, and complexity. Therefore, research to accelerate data handling, to provide better ways to structure CIM systems, and to provide better means of classifying system components can have an enormous impact by allowing CIM to conform to the needs of the manufacturing environment.
- Much of manufacturing is based on experience rather than on systematized scientific knowledge. Therefore, opportunity exists for research to identify and formalize manufacturing objects at progressively higher levels of abstraction. This calls for an overall CIM architecture and generic tools for building advanced CIM.

NOTES

1. Committee on Science, Engineering, and Public Policy, National Academies of Sciences and Engineering, "Report of the Research Briefing Panel on Computers in Design and Manufacturing" (Washington, D.C.: National Academy Press, 1983).

2. Panchathanthra. The illustration was done by Reginald Pollack, based on illustrations by Janice Holland for The Blind Men and the Elephant, retold by Lillian Quigley (New York: Charles Scribner's Sons, 1959).

3. Among the recent reports and conferences that include research topics for CIM are the following:

   Committee on the CAD/CAM Interface, National Research Council, Computer Integration of Engineering Design and Production: A National Opportunity (Washington, D.C.: National Academy Press, 1984).

   Manufacturing Studies Board, National Research Council, Toward a New Era in U.S. Manufacturing: The Need for a National Vision (Washington, D.C.: National Academy Press, 1986).

   National Academy of Engineering, U.S. Leadership in Manufacturing (Washington, D.C.: National Academy Press, 1982).

   Richard Volz and Arch Naylor, Workshop on Manufacturing Systems Integration, November 6-8, 1985, St. Clair, Michigan.

   H. Bloom and N. Kuchar, editors, A National Forum on the Future of Automated Materials Processing in U.S. Industry--the Role of Process Models, Artificial Intelligence, and Computer Integration, May 19-20, 1986.

   National Academy of Engineering, Conference on Design and Analysis of Integrated Manufacturing Systems (Washington, D.C.: National Academy Press, March 1988).

   National Bureau of Standards, Future Research Agenda for the Automated Manufacturing Research Facility, workshop held November 1985.

   National Science Foundation, Research Priorities for Proposed NSF Strategic Manufacturing Research Initiative, March 11-12, 1987, Orlando, Florida.

4. For example, an Engineering Foundation Conference on Computer-Integrated Manufacturing is planned for 1988.

5. For a survey of such taxonomies, see H. Van Dyke Parunak and John F. White, A Synthesis of Factory Reference Models (working paper, Industrial Technology Institute, September 24, 1987). One specific taxonomy is presented in Joseph Harrington, Jr., Understanding the Manufacturing Process: Key to Successful CAD/CAM Implementation (New York and Basel: Marcel Dekker, Inc., 1984).

6. The nature and magnitude of the potential benefits of CIM are discussed in Thomas G. Gunn, Manufacturing for Competitive Advantage: Becoming a World Class Manufacturer (Cambridge: Ballinger, 1987)

and Committee on the CAD/CAM Interface, National Research Council, Computer Integration of Engineering Design and Production: A National Opportunity (Washington, D.C.: National Academy Press, 1984).

7. Forward inference starts with what is known to be true and deduces subsequent expressions until it eventually proves a desired conclusion. Backward inference starts with a conclusion and hypothesizes sufficient preconditions until it eventually reaches what is known to be true.

8. Annealing is the process of slowly decreasing the temperature of a thermodynamical system while random thermal motions allow it to settle into a low energy state. Simulated annealing sets up an analogy between such a system and a computational problem. Solutions to the problem are randomly perturbed while a variable analogous to temperature is gradually decreased, until the solutions settle at a near optimum.

9. For example, the Initial Graphics Exchange Specification (IGES), Product Data Definition Interface (PDDI), and Product Data Exchange Specification (PDES) were progressive efforts to standardize the data used for design and manufacture.

10. Kenneth Flamm, Creating the Computer (Washington, D.C.: The Brookings Institution, 1988), p. 1.

11. These topics are based in part on the research agenda of ESPRIT-CIM. This area of the European Strategic Planning for Research in Information Technology program is described in R. W. Yeomans, A. Choudry, and P. J. W. Ten Hagen, Design Rules for a CIM System (Amsterdam: North-Holland, 1985).

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