COLLEGE OF ENGINEERING
THE UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

A PROPOSAL TO THE **MICHIGAN RESEARCH EXCELLENCE FUND** TO ESTABLISH A **CENTER OF SCHOLARLY EXCELLENCE IN COMPLEX MANUFACTURING TECHNOLOGY**

March 1985

ABSTRACT

The University of Michigan College of Engineering seeks $5 million in base support from the Research Excellence Fund to enhance and sustain its activities in complex manufacturing technology. Numerous State of Michigan studies have singled out the unique role of UM Engineering in this effort, including the Governor's Task Force for a Long-Term Economic Strategy for Michigan which recommended:

> "To ensure the lead position in the development of manufacturing production processes, Michigan must invest heavily in centers of applied research in industrial technology, with special emphasis on developing the University of Michigan College of Engineering as a world leader in this field."

The University proposes to expand its ongoing Center for Research in Integrated Manufacturing to better address not only the elements of complex manufacturing technology, but especially their integration. The Center will address industrial problems in the four interrelated areas of: product design, cell-level production, plant-level production, and strategic management. Activities in each of these efforts with be tightly coordinated to address industrial needs for improving productivity, quality, and the worker environment to enhance the competitiveness of Michigan industry.

The proposed Center is designed to take full advantage of the UM's unique strengths: the Computer-Aided Engineering Network (an advanced distributed environment in UM Engineering), close links with the Industrial Technology Institute, and establish connections with automotive and durable goods manufacturers. UM's research ideas will be pursued initially within the automotive and industrial electronics industries and later in other transporation and electronics, providing a cross-fertilization of manufacturing research germane to both mechanical and electronic systems.

A significant element of the Center will be engineering education in complex manufacturing technology. To attract, retain, and development human resources for the next generation of manufacturing systems, UM will take innovative steps in undergraduate, graduate, and continuing education. The impact on education will be enhanced through a Statewide network of engineering colleges.

The support requested from the Research Excellence Fund will enable the Center to perform large-scale system integration, to provide long-term stable infrastructural support, and to create the incentives for faculty and student professional involvement in emerging industrial technology.

1. AN INVESTMENT IN ENGINEERING EXCELLENCE

There is strong evidence to suggest that a primary catalyst and necessary ingredient in technology-based industrial development is the presence of a world-class engineering school. Such institutions provide not only the outstanding engineering graduates necessary to sustain and strengthen the competitiveness of existing industry; in addition, they supply the technological innovation and entrepreneurs necessary for building new industry.

The presence in the State of Michigan of one of the nation's leading engineering schools, the University of Michigan College of Engineering, is of critical importance of its future economic prosperity. Michigan requires a massive infusion of new technology if it is to regain its traditional industrial and economic leadership and become the nation's source of emerging industrial technology, the world's leader in complex manufacturing processes. Our state must use technology to revitalize and diversify its present industrial base to protect existing jobs, even as it seeks to spawn and attract new industries over the longer term to create new jobs for Michigan citizens.

The dominant role played by world-class engineering schools in economic development has been identified in study after study. In California and New England, most of the signficant technological innovations behind industrial growth originated in key local engineering schools and their associated research laboratories (e.g., MIT, Stanford, UC-Berkeley, and Caltech). These innovations were typically exploited by new firms established by faculty, staff, and graduates of these schools. Companies with origins in these schools subsequently formed the basis of powerful agglomerations of new industries. Furthermore, these schools attracted the massive federal research contracts which played the key role of "risk capital" in building new industries such as electronics and aerospace.

In each case, the key engineering schools involved were top-flight institutions conducting research at the cutting edge of new technology. Furthermore, these schools were oriented to the commercial applications of their innovations, provided the entrepreneurial environment necessary for technology transfer, and attracted the federal funding necessary to stimulate such industrial development.

It is reasonable to expect that the role of a world-class engineering school will be even more critical in a future increasingly dominated by science, technology, and information. There seems little doubt that Michigan`s ability to strengthen and diversify its industrial base, to compete for new industry and economic growth, and to create the jobs necessary for Michigan's long-term prosperity will depend on its success in building and sustaining such an institution.

The University of Michigan College of Engineering provides

Michigan with both a vehicle and an extraordinary opportunity for investing in the long-term economic health of the state. As one of the leading engineering schools in the nation today, the College is regarded as one of the few institutions in the world capable of achieving the degree of excellence in science and technology ncessary to have a major impact on economic development.

More specifically, the present status of the UM College of Engineering can be summarized as follows:

Reputation: 5th in the nation
Capacity: 6,000 students, 320 faculty (3rd in the nation)
Productivity: 1,250 BS, 550 MS, 100 PhD degrees annually
Research: $25 million per year (federal and industrial)
Student Quality: 98th percentile (1280 SATs, 3.8 GPAs)
Faculty Quality: Outstanding (energetic and innovative)
Physical Plant: Rapidly improving
Laboratory Equipment: Seriously deficient
Base Funding: Seriously deficient

Over the years, UM Engineering has had a major impact on Michigan's economic prosperity:

- o Each year the College graduates over 1,800 engineers, of whom roughly 70% remain in the Great Lakes area.

- o UM Engineering has been recognized as a national center of excellence in several areas of importance to Michigan, such as complex manufacturing technology, ergonomics, advanced electronics and optics, and computer engineering.

- o The College has formed important research partnerships with Michigan companies across a broad range of technologies.

- o Over the past three decades, the College and its affiliated research laboratories have spawned over 85 companies employing 40,000 Michigan citizens and generating over $2 billion per year in sales.

- o UM Engineering faculty and staff are accelerating the rate at which they spin off new companeis (7 in 1984).

The UM College of Engineering today is in an excellent position to achieve national leadership in areas of major importance to Michigan's future including complex manufacturing technology, advanced electronics and optics technology, and machine intelligence and information technology. However, if the College is to have the capacity to respond to such needs and opportunities, it will require direct and immediate assistance from the State of Michigan to restore an adequate base level of support for its programs through initiatives such as the Research Excellence Fund.

2. MICHIGAN: THE NATION'S SOURCE OF EMERGING INDUSTRIAL TECHNOLOGY

2.1. The Challenge

Numerous studies have suggested that Michigan's economy will continue to be driven for the foreseeable future by durable goods manufacturing. However it is essential that this industry shift rapidly to complex manufacturing processes less vulnerable to low-wage competition. Michigan's future economic prosperity will depend on its becoming America's "factory of the future", its leading source of emerging industrial technology. In contrast to other regions of the country in which "high tech industries" are regarded as a separate industrial sector, in Michigan new technology will be at the heart of every industrial sector.

However, there is another equally important aspect of technology-based economic development for our state. Experience has shown that a primary source of new jobs is the creation of new companies and industries. And while durable goods manufacturing will continue to provide the basis of this state's economy in the near term, it is essential that Michigan stimulate and nurture the growth of new industries that will diversify and strength its economy for the long term. It is logical to expect that advanced technology and innovation will play the key role in bulding these new companies and creating new jobs.

In summary, then, Michigan faces two major challenges: First, our state must take actions to protect its present economic base by strengthening the competitiveness of existing industries such as the automobile and automotive supplier industry. Second, it must establish an environment capable of attracting or stimulating the growth of technology-based industries that can provide new jobs for Michigan citizens. Key in both efforts will be the availability of centers of excellence and innovation in key areas of technology related to manufacturing

2.2. The University of Michigan Response

As a leading university in the heart of this nation's manufacturing industry, the University of Michigan has made a major commitment to work closely with industry and government to help revitalize and diversify the manufacturing base of this nation in general and the State of Michigan in particular. Two recent initiatives, the Center for Research for Integrated Manufacturing (CRIM) formed within the UM College of Engineering, and the Industrial Technology Institute (ITI), formed to provide an interface between academe and industry, stand out as major accomplishments of these efforts. Both institutions focus on computer-integrated manufacturing systems, including design, production, and the effective and safe use of humans, machines, and resources.

Although CRIM has been fortunate in establishing itself as a nationally recognized center of excellence in manufacturing technology and obtaining strong industrial and federal support, its lack of large, sustained support has hampered its progress. Furthermore, since it must rely on the human resources of the UM College of Engineering, the serious underfunding of the College in recent years has made it increasingly difficult to attract the engineers and scientists necessary for the conduct of such a world-class research programs.

In this proposal, the University of Michigan seeks a level of base, sustained support for the UM College of Engineering to allow it to broaden and sustain its position of leadership in complex manufacturing technology.

3. A PROPOSAL FOR A NATIONAL CENTER OF EXCELLENCE IN COMPLEX MANUFACTURING TECHNOLOGY

The University of Michigan seeks a commitment of $5 million per year in base funding to build and sustain its Center for Research on Integrated Manufacturing into a national center of excellence in complex manufacturing technology. Of this amount, $4 million per year will be necessary to attract and support the faculty and staff necessary to conduct these research programs and related technology transfer activities. In addition, a base commitment of $1,000,000 per year will be necessary to leverage the massive industrial and federal contracts, grants, and gifts necessary to equip state-of-the-art laboratories in emerging industrial technology.

3.1. Theme and Rationale

Strong State support would enable the Center for Research on Integrated Manufaturing to take bold steps toward strategic system integration in manufacturing systems beyond those that universities have customarily been able and willing to take. The theme and rationale for this expansion of CRIM activity is based upon the realization that effective industrial competitionr equires strategic vision and action. A recent University of Michigan study cited four major driving forces in industrial competition: (1) consumer demand for product diversity, (2) flexible manufacturing systems, (3) rapidly evolving technology, and (4) internationalization. Compared with its major industrial rivals, the United States is relatively weak in labor-management cooperation, innovation in mature industries, comparative manufacturing costs, experience in global markets, and workers' general education, particularly in mathemtics and science.

It is clear, therefore, from an engineering perspective that we should look at both the unprecedented opportunities offered by technology, yet not lose sight of the socioeconomic contexts within which this technology can make its contributions to international competiveness. CRIM will include in its scope not only technological developments in areas such as computer aided design and manufacturing (CAD/CAM) and flexible manufacturing control but also the human-oriented, non-technical issues, such as the optimal sue of equipment and an organizational and behavioral understanding of using new integrated manufacturing technology to increase productivity, quality, and worker safety. We need to make specific suggestions to the strategic decision makers in indusry how new manufacturing technology can be used as their competitive weapons. Inasmuch as academic time and resources are limited, we also need strategic guidance of research and educational activities within engineering colleges in integrated manufacturing.

Based on the above rationale, the main theme for the Center for Research on Integrated Manufacturing will be the improvement of manufacturing productivity, quality, and worker environment through a comprehensive and integrated approach to the manufacturing system.

3.2. The Concept

Although a complete manufacturing cycle that follows the creation of the product from its conceptualization to its shipping includes many steps, the anticipated technological breakthroughs for integrated manufacturing, with profound implications for international competitiveness, center on the integration of product design, cell-level production, and plant-level production. We propose, therefore, to focus CRIM activities on these three technical activities, their interrelationships, and their strategic management, as shown in Figure (recognizing that other steps in the manufacturing cycle, such as purchasing, servicing are important but not central to the CRIM thrust).

The horizontal dimension in Figure is time. As a manufacturing company moves through its product planning cycle (from strategy to execution), the emphasis of its technical activities shifts from product design, responding to market demand, to production system planning and control. The purpose of strategic management of these technical activities is to use the capabilities of integrated manufacturing to meet global competition.

To concentrate on truly significant improvements, CRIM will be guided by the following goals:

- Conduct research to achieve quantum jumps in the next generation of computer-integrated design and manufacturing systems.
- Demonstrate the strategic utility of such systems in industrial settings.
- Educate a new breed of engineer who can contribute to the above.

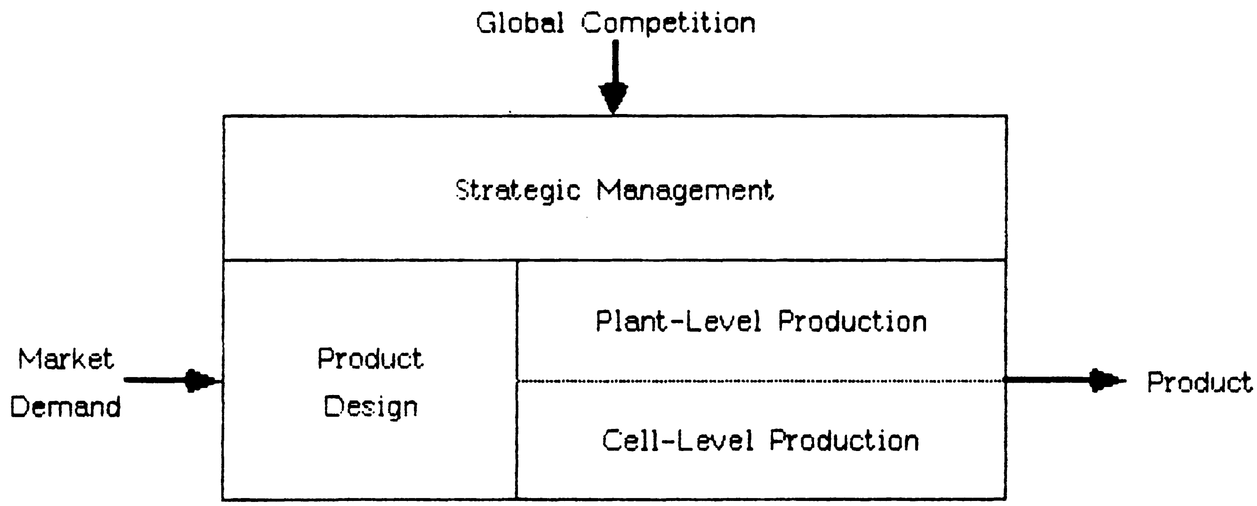

Figure Scope of Proposed Research on Integrated Manufacturing

3.3. The Approach

The CRIM approach will be cross-disciplinary research and education to enhance manufacturing productivity, quality, worker safety, and international competitiveness. Cross-disciplinarity will be fostered by concentrating on significant generic problems at the interfaces of the interrelated activities in Figure and by using specific manufacturing system testbeds to try out generic solutions. The term "generic" represents the set of problems between basic research problems at one extreme and specific applied problems at the other.

This approach represents a tremendous challenge for a modern American university, given the long history--and a proud one--of doing largely the opposite: focusing on the separate parts of large systems through research and education in individual disciplines. The UM College of Engineering, however, in concert with the State of Michigan, has clearly begun to meet this challenge.

To build on the current momentum and reach the more ambitious goals noted above, we intend to take the following specific approach:

We will expand CRIM into a major center that can perform large-system integration in manufacturing. The expanded CRIM will establish new research areas as well as build on existing research on components and subsystems sponsored by a number of private companies (e.g., IBM, GM, and General Dynamics) and public agencies (e.g., NSF, AFOSR, NASA, ARO). CRIM research will be aimed at producing demonstrable solutions to generic problems in integrated manufacturing. The demonstrations will be based on experimental reseach in a number of manufacturing system testbeds, some on or near the UM campus, others in industry. Educational links and industrial involvement in CRIM research will permeate all projects.

3.4. Management and Organization

Leadership and management coordination are so critical to cross-disciplinary research centers that how these issues are resolved has largely determined their success or failure. Cross-disciplinary research requires a change in the behavior of normally discipline-oriented university researchers. They must learn each other's language, methodology, and conceptual framework. They must communicate continuously with each other and with industry and adjust to new modes of research management.

While cross-disciplinary research and education in the past have been difficult and not particularly successful in universities, the circumstances surrounding the CRIM have elements that augur well for success, and the UM approach to management and organization is designed to stress these positive elements.

First, the link between research and education required by CRIM, once firmly established, will increase the stability of the Center within the University. Second, industrial involvement, if managed properly, will provide an added dimension for evaluating faculty accomplishments, jobs and career opportunities for students, and possibilities of stable and leveraged funding--all of which have been difficult for cross-disciplinary centers to achieve. And, finally, engineering faculty members, unlike their colleagues in pure sciences, are problem-oriented and therefore motivated to do cross-disciplinary work.

Figure is an organizational chart of the expanded CRIM, carefully designed to emphasize three defining characteristics: system integration, educational linkage, and industrial interaction. To ensure system integration, the new CRIM will not be divided into divisional subunits. Instead, its leadership will reside in a Management Committee charged with planning, resourcing, and controlling all CRIM activities. The same committee will coordinate these activities with the normal educational functions within the College and with other CRIM projects supported by government agencies and individual companies.

The two blocks on the right side of Figure represent an organizational design for industrial interaction. The External Advisory Board will include industrial executives who, from perspectives external to UM, will advise the Center on its policies and directions. They will review CRIM's overall program plans and accomplishments, inform CRIM's director about industrial trends, and suggest specific opportunities for the Center' industrial involvement in both research and education. The Project Steering Committee will include technical and managerial people from industry to work with CRIM's Management Committee to set specific project goals, to review and steer the research and associated educational linkages.

The Internal Advisory Board will advise the Center from perspectives internal to UM and will suggest specific disciplines and talents for the Center to draw from. The members of this Board will include the University Vice-President for Research, the Engineering Associate Dean for Academic Affairs, chairmen of selected departments (EECS, MEAM, IOE, Aero, MME, etc.), and heads of selected programs and centers e.g., the Center for Ergonomics). The Center's Management Committee will intereact with the curricula and graduate committees in the relevant departments to coordinate course development and revision, Ph.D. qualifying examination requirements, and other educational links in the CRIM activities.

3.5. The Research Areas

Improvement of productivity and quality for the U.S. manufacturing sector today is frequently defined as a set of instrumental goals:

- Shorter lead time for the product development cycle.
- Error-free design and design for manufacturability.
- Flexible manufacturing for a diversity of products.
- Higher yield and less scrap (making it right the first time).
- Reduction of work in process and inventories.
- Safe and desirable workplace.

This set of industrial needs, along with the major technological opportunities on the horizon, helped us define four research areas:

Research Areas	Central Features
(A) Product Design	o Computer-aided integration for creative and optimum design
(B) Cell-Level Production	o Integration of sensors and intelligent control at the cell level
(C) Plant-Level Production	o Information and physical flow control and planning at the plant level
(D) Strategic Management	o Strategic technology assessment, planning, and interventions.

These four research areas, presented in detail in Appendices A and D, are closely coupled. Figure 2.2 shows their linkages. Since the use of computers is central to the implementation of integrated manufacturing, a distributed structure of computer control of manufacturing systems, as shown in Figure 2.3, will help explain the linkages. The letters A, B, and C in Figure 2.3 indicate the relevant portions of the diagram corresponding to the first three research areas. (Note that not all the contents of the three research areas, nor those of the fourth area, are included in Figure 2.3). Combining Figures 2.2 and 2.3, we may tabulate the linking features of the four research areas as follows:

The large circle surrounding the square in Figure 2.2 is the supporting research required by all four areas. It is essential that there be a commonality and comprehensiveness to the database resources. It will become increasingly important that the large number of distributed computers in factories be operated, at each level of the computing hierarchy, as a distributed computing system rather than a distributed system of computers. CRIM will also look for opportunities across all areas to develop and apply artificial intelligence techniques, such as expert systems, to integrated manufacturing.

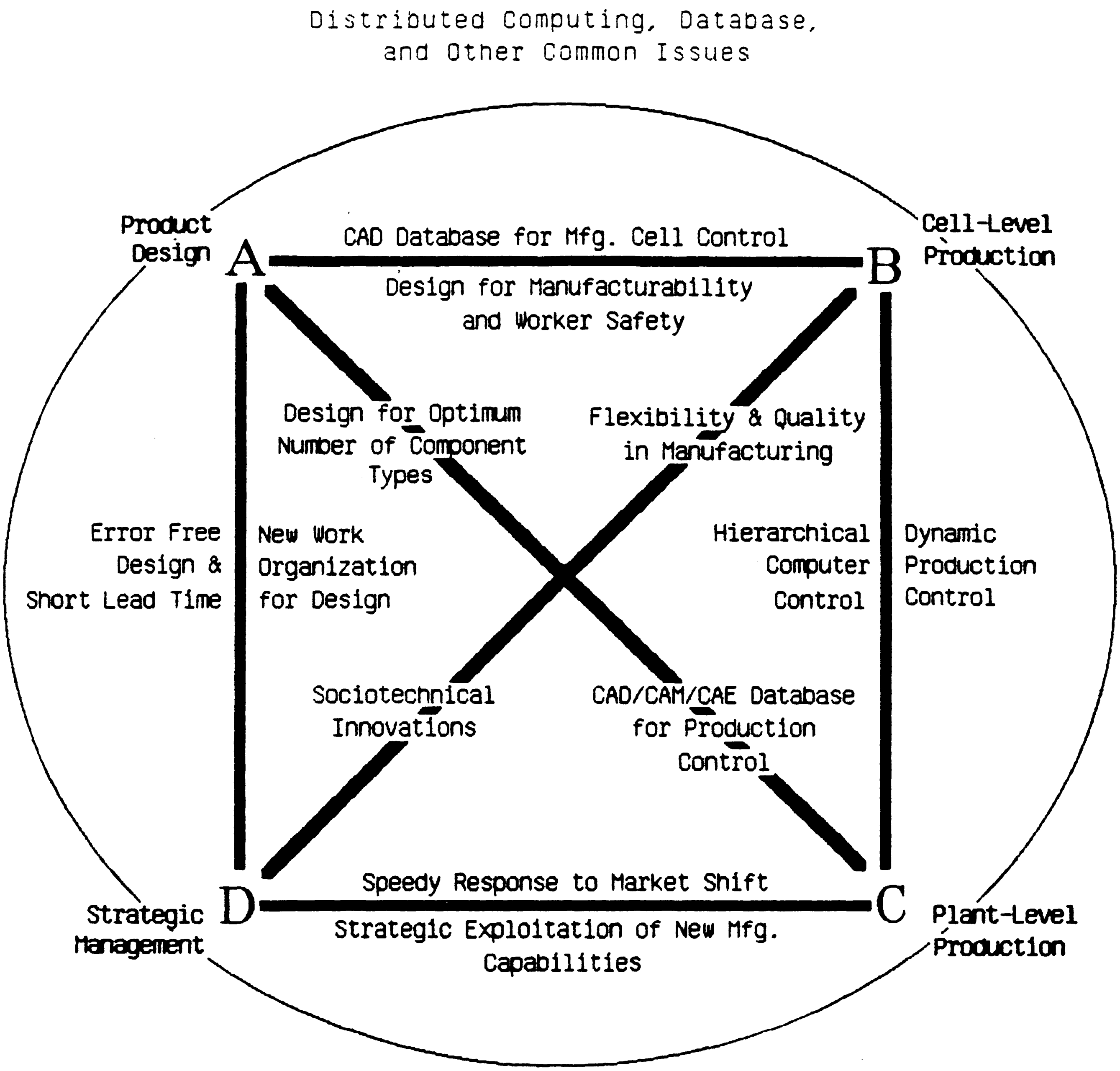

Figure , Illustrative Interactions Among the Four Research Areas

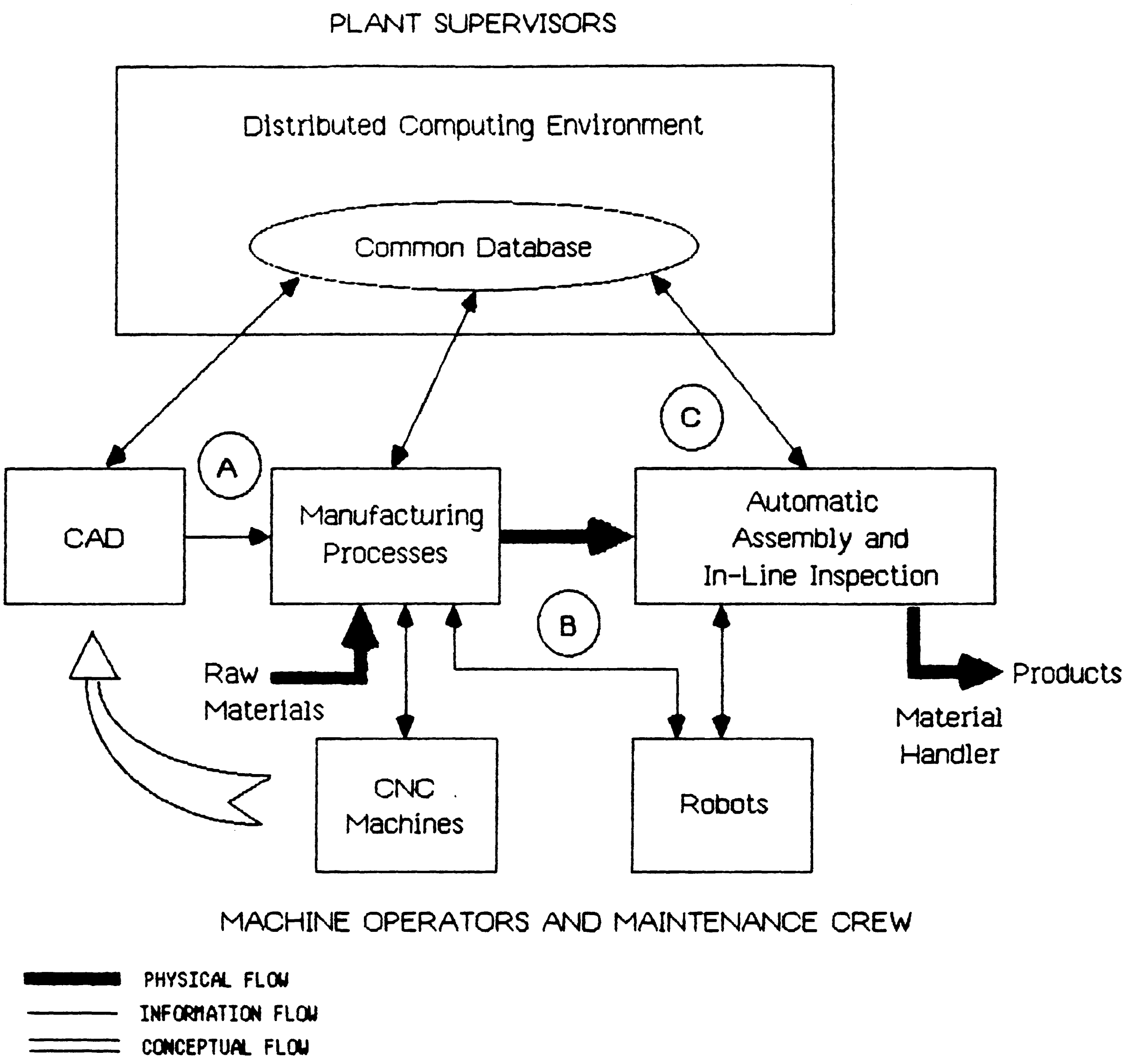

Figure Structure of Computer Control of Manufacturing Systems

Our research plans have benefited from significant industrial input, especially from company representatives who have agreed to serve on the Center's External Advisory Board and on the Center's Project Steering Committee. These research plans will be modified and developed into a cluster of projects as greater industrial involvement takes place after the ERC is established. Indeed, we expect some modification of these plans to occur in the course of further industrial interactions. For this reason, and for the maintenance of program flexibility, the research descriptions in Appendices A through D indicate only preliminary research directions and approaches and the commitment of our core faculty to serve as co-investigators. The plans leave room for adjustments and adaptations stemming from industrial interactions and changes in future research needs.

We intend to test our research ideas on transportation and electronics industries. Initially, the testing will be on two major industries--automotive and semiconductors. The UM's connections with these two industries are exceptionally strong, and the on-campus manufacturing system testbeds are suitable to the generic problems of the two industries. Moreover, the auto industry designs and uses a large number of integrated circuits. The choice has other merits as well. In the auto industry, manufacturing has been driven mainly by design, while in the semiconductor industry, design has been driven mainly by manufacturing. In order words, design for manufacturability has been a cardinal principle in the semiconductor industry: the designer of integrated circuits has to follow a set of rules dictated by the capability of the semiconductor manufacturing process.

Similar rules are not nearly as sophisticated in the auto industry. On the other hand, three-dimensional mechanical design in the auto industry has always been sophisticated, and the electronic designer may have something to learn from the mechanical designer as the former gets more involved in three-dimensional problems. In terms of the technoculture, the two industries are quite different in their age, labor relations, capital structure, and organizational characteristics. Thus, an interplay between the two industries in our integrated research can be expected to yield an interesting cross-fertilization of ideas. In addition, we expect to involve the manufacturers of manufacturing systems, including machine tool and robot manufacturers, as well as manufacturing software companies.

3.6. The Integration Mechanisms

Conceptual, physical, and organizational integration mechanisms will be used to ensure integration in the proposed expansion of CRIM:

- o Interrelate all proposed work within an overall system framework.

- Focus proposed work on real industrial problems.
- Demonstrate research results on system-level testbeds.
- Use a next-generation distributed computing environment as the basis for system integration.
- Include researchers from different disciplines in the same project.
- Use management and budgetary control to ensure interrelated projects.
- Encourage dialogue between researchers with different viewpoints.

The linking features of the four research areas, as summarized in Figure 2.2, will provide the overall framework for integration. The framework, to be updated from time to time, will be used to identify and screen proposed projects and interrelate the results of chosen projects.

Focusing on well-defined problems is the general underlying principle for cross-disciplinary research. While this principle has worked well for mission-oriented programs in both industry and government, a creative adaptation is needed in the academic environment where the tradition leans toward solitary endeavors in fundamental research and transmitting knowledge. CRIM research, therefore, will be focused on a demonstration of solutions to <u>generic</u> problems of integrated manufacturing.

We propose to use several interrelated <u>testbeds</u> as an important integration mechanism. Each testbed will be fairly large, incorporating, to various degrees, many facets of an entire manufacturing system. Each will be a prototypical example of a manufacturing system, presenting the generic problems of all such systems. Naturally, there is a limit to how many testbeds an CRIM could support, particularly if each had to be developed <u>de novo</u>. Fortunately, the UM already has several excellent component-level testbeds on campus, including the equipment and systems in the Robotics Research Laboratory and in the Machine Tool Diagnostic Sensing and Control Laboratory within CRIM.

Moreover, we have access to an automated manufacturing facility in the final stages of completion at the Industrial Technology Institute. A larger facility of the same kind to be developed by ITI in its new quarters adjacent to the Engineering Campus will likely become an important testbed when completed. The two ITI facilities will also provide opportunities to study the coordination of two geographically separated facilities.

Another system-level testbed is an integrated circuit fabrication line currently being developed by UM's Solid-State Electronics Laboratory for the Semiconductor Research Corporation. This facility will be available for experimental research on manufacturing systems for microelectronics.

The previously described Computer-Aided Engineering Network, with powerful graphics capability, distributed database, and access to supercomputing facilities, is another significant testbed for large-system integration, especially for computer-aided design activities and local area network concepts, for both research and pedagogical purposes. The computer network is also an integration mechanism in itself, since any substantive interactions via the network will have to be based on common languages, shared databases, consistent logic, and compatible hardware. CAEN has the potential of further expansion, with optical fiber links to the various testbeds on or near the UM campus, to provide testbeds for large-scale higher-level system integration in CRIM activities.

3.7. Industrial Interactions

Industrial interactions will be important for both research and education. They are necessary to ensure that the research performed is relevant to international competitiveness, toincrease the usefulness of research results, to provide meaningful testbeds for manufacturing systems, and to develop joint and complementary research between CRIM and industry. They are necessary, likewise, to increase the industrial relevance of manufacturing engineering education, to facilitate technology transfer, and to coordinate the development of engineering human resources in both industry and universities.

To achieve meaningful, continuing, and in-depth industrial interactions, we propose three levels of industrial involvement in the Center:

(1) External Advisory Board (policy level)

(2) Project Steering Committee (project level)

(3) Substantive participation in research and teaching (task level).

The functions and memberships of (1) and (2) are discussed in Section 2.1 on management and organization. Substantive participation by industry people will be at the task level--cooperative research tasks, guest lectures and seminars, and experimenting with ideas on various testbeds on campus or at industrial sites.

While we have been quite successful in industrial interactions at all three levels discussed above, to reach CRIM program goals, these interactions need to meet a new two-part challenge: system integration and research-education synergism. The letters of endorsement from the key companies already committed to in-depth involvement in CRIM research and education, indicate their understanding of this challenge and their intention to help us meet it.

While we are pleased with the industrial interactions we already have at this time, we plan to make continuous efforts to extend and deepen them, especially after State funding is assured. Specifically, we will give frequent briefings to selected companies interested in integrated manufacturing (we have given briefings to over 60 companies in the last two years, and we plan to hold annual research conferences that will attract additional companies that may wish to interact with us at any of the three levels. Furthermore, our experience corroborates the findings of NSF's research on industry-university cooperative research. Specifically, successful cooperative projects rest on an existing foundation of social and professional exchange between university and industry participants. For the purpose of nurturing such exchanges, the Center will allocate a certain portion of its CRIM support to fund selected faculty on a number of "getting-to-know-you" projects, through which they will work informally with their industrial counterparts on critical portions of the system-integrative research agenda determined by the Management Committee.

Recognizing the ITI connection as one of our unique strengths, the Center will seek indirect industrial interactions (especially with small and medium-sized firms) through ITI to complement the Center's direct interactions with major companies. A tangible form of this indirect interaction may be a three-way tie among Center-ITI-industry on those projects that are particularly system-oriented. Furthermore, CRIM has been engaged in a number of projects, and expects to have many more, sponsored by individual companies (IBM, GM, General Dynamics, etc). We anticipate synergism between the CRIM-supported projects on generic problems and the individual-company-supported projects on specific applications. As evidenced by the letters in Appendix H, some of our current project sponsors consider that CRIM support will not replace their sponsorship but instead will enhance the benefits they derive from the projects they are now sponsoring, and they are, therefore, likely to support us even more in the future.

3.9. Specific Budget Requests

Specific budget requests for staffing and equipment are provided in tables I, II, and III.

TABLE I

BASE BUDGET NEEDS

CENTER FOR RESEARCH ON INTEGRATED MANUFACTURING

Staffing	
Faculty participants: 26 FTEs	$2,340,000
Technical support staff: 12 FTEs	360,000
Graduate research assistants: 32 FTEs	800,000
Laboratory equipment (sustained needs)	1,500,000
Total Base Budget Needs	$3,500,000

TABLE II

LABORATORY EQUIPMENT NEEDS

TABLE III

STAFFING REQUESTS:

Faculty Participants		26 FTEs
Manufacturing Systems		
Mechanica Engineering	5	
Industrial Engineering	2	
Electrical Engineering	5	
Software and Systems Engineering		
Software Engineering	2	
Artificial Intelligence	2	
Networks, Communication	2	
Manufacturing Processes		
Materials Characterization	2	
Materials Processing	2	
Advanced Materials	2	
Advanced Processes	2	
Technical Support Staff		12 FTEs
Graduate Research Assistants		32 FTEs

4. CONCLUDING REMARKS

There is ample evidence across this nation to demonstrate the impact that world-class engineering schools have on economic development. A major investment by the State of Michigan in the UM College of Engineering through the Research Excellence Fund can be expected to have a similar impact on our State's long-term economic prosperity. Furthermore, since the most talented of Michigan's high school graduates now enroll in the College, such action would also represent an important investment in Michigan's most valuable resource, its youth. These extraordinarily talented students will become the leaders and bulders of Michigan industry. Not only will they sustain the competitiveness of existing Michigan companies, but they will found the new companeis necessary to diversify Michigan's economic base.

The UM College of Engineering is unique in this State in its ability to attract outstanding facilty and students necessary to achieve national leaderhsip. Furthermore, it alone possesses the reputation to leverage this investment of State support several-fold through federal and industrial grants and contracts.

The requested investment of $5.0 million in base support of a center of scholarly excellence in complex manufacturing technology through the University of Michigan Center for Research on Integrated Manufacturing is modest compared to the almost certain economic impact of such activities. Furthermore, such an investment is necessary if the State of Michigan is to respond to the commitments made both by Michigan industry and the federal government in the UM College of Engineering.

Roughly 70 years ago, the automobile industry originated in the inspired inventions of self-educated craftsmen skilled in building engines for boats and machinery. The industry took root in Michigan and triggered the economic growth which led to the impressive social institutions characterizing our State today. However, recent patterns of economic development such as Silicon Valley and Route 128 suggest that future industrial growth will be stimulated less by physical capital than by intellectual capital -- by technological nnovation, the talented engineers capable of understanding and applying this technology, and the entrepreneurs capable of stimulating industrial growth.

Leading engineering schools such as the UM College of Engineering are the key sources of these essential ingredients for technology-based economic development. it is from this perspective that the UM College of Engineering must be viewed as one of the most important investments Michigan can make for its long-term economic prosperity.

APPENDIX A

THE IMPORTANCE OF NECESSARY "INFRASTRUCTURE" SUPPORT

While the support of research "Centers of Scholarly Excellence" are of major importance to Michigan's future, it is essential to recognize that such Centers will only be successful if the State restores a adequate level of base funding to sustain the "infrastructure" of the parent academic unit. Perhaps nowhere is this more apparent that in the crisis presently faced the the University of Michigan College of Engineering.

The importance of world-class engineering programs to economic development has been recognized by state after state. One by ones, states such as Illinois, Ohio, Pennsylvania, Minnesota, Indiana, and New York have made massive commitments to build the MITs, the Berkeleys, and the Stanfords of tomorrow. They have recognized that only nationally competitive engineering schools are capable of a major impact on economic development, since only such world-class programs are able to attrct the outstanding faculty, the students, and the economic and technological resources necessary to stimulate the growth of new industry.

But, Michigan, unlike most of these other states, already has an institution with a competitive edge, the UM College of Engineering. Ironically, our state also stands apart from others in its failure thus far to restore an adequate level of support to its premier engineering school. During a decade in which enrollment int he College grew by over 45% to its present level of 6,000 students, the level of state funding for its programs has dropped dramatically. The College is currently understaffed by at least a factor of two relative to state formula funding models. This has led to a seriously overloaded faculty and limited opportunities for reserach and spinoff activities. Furthermore, technical support staff and equipment funds were cannibalized to offsset the deterioration in state support, and this has resulted in obsolete and inadequate laboratories and an equipment and computer inventory backlog now estimated at over $70 million.

Despite its importance to Michigan, the College's capacity to respond to the needs of Michigan and its citizens has been serously crippled by inadequate state support. More serous is the probably consequence that over the next several years the College will be forced to cut enrollments by as much as 50% and dismantle programs of critical importance to this state if this chronic underfunding cannot be reversed.

To calibrate the magnitude of this underfunding, it should be noted that the UM Engineering College receives an annual instructional budget of roughly $3,900 per student, compared to levels of $5,500 in most public peer institutions (Illinois, Purdue, Wisconsin,...) and an increasing number of emerging institutiosn (Texas, Arizona, Florida, Maryland,...). In sharp contrast, the leading engineering institutions such as UC-Berkeley, MIT, and Stanford receive roughly $7,000 per student for their instructional programs -- twice that provided to UM Engineering. It is evident that unless this serious funding gap is erased, the UM Engineering College will find it increasingly difficult to compete for the faculty and other resources necessary to achieve the national leadership required for maximum economic impact.

If the University of Michigan College of Engineering is to have the capacity to participate in positioning Michigan as the leader in merging industrial technology, it will require direct and immediate assistance from the State of Michigan to restore an adequate base level of support for its programs. University officials, working closely with leaders from State government, business, labor, and industry, have developed the following two-stage plan for special action:

State I (the "restoration" phase) of this plan would involve the rapid restoration of a level of State support for UM Engineering comparable to that presently received by other peer and emerging public institutions. Since UM Engineering's level of General FUnd support per student ($3,900) presently falls $1,600 behind these institutions, such action will require a base budget increase of $8.5 million (allocated both to staffing and sustained equipment support). Additional one-time support of $20 million will be required to support major initiatives in the critical areas of complex manufacturing technology, advanced electronics and optical devices, and advanced materials.

In Stage II (the "leadership" phase), a sequence of State investments would bring the support of UM Engineering to a level comparable to that of leading engineering schools (e.g., UC-Berkeley, MIT, Stanford, UCLA). This will require an additional increase in base appropriations of $9.5 million (bringing the General Fund support per student to $7,000) and one-time equipment support of an additional $20 million to restore the College's laboratory equipment inventory to competitive levels. In additiona, two new physical facilities would be required: a $20 million bulding to house laboratories for rapidly changing areas of technology, and a $20 million facility to serve as an incubation center for bringing together startup companies and satellite corporate R&D laboratories with College faculty, students, and staff.

It should be noted that the UM College of Engineering is unique in this State in its ability to attract the outstanding faculty and students necessary to achieve national leadership. Furthermore, it alone possesses the reputation to leverage this investment of State support several-fold through matching grants and contrcts from both the federal government and the private sector. More specifically, the proposed investment by the State would be matched by growth in College-generated revenues to a sustained level of over $70 million per year: $30 million per year from federal and industrial research contracts; $25 million per year from student tuition and fees; and $15 million per year from private and corporate gifts such a partnership involving State, federal, and private support is essential in achieving the level of resources necessary to compete with the nation's leading public and private institutions.

APPENDIX B

THE IMPACT OF THE UM COLLEGE OF ENGINEERING ON STATEWIDE ECONOMIC DEVELOPMENT

Background:

In recent months, several important new studies have been released which have clarified:

- The importance of technology to Michigan's future economic development.
- The investments that will be necessary if Michigan is to participate in this nation's long-term prosperity.
- The role that higher education will play in this effort.

These studies include:

1. Putting our Minds Together: New Directions for Michigan Higher Education, The Governor's Commission on the Future of Higher Education in Michigan (the "Ross Report")
2. The Path to Prosperity, Findings and Recommendations of the Task Force for a Long-Term Economic Strategy for Michigan
3. Preliminary Recommendations, Governor's Commission on Entrepreneurship and Small Business Development
4. Route 128 and Silicon Valley: A Comparison, Peter Eckstein, Executive Director, Governor's Commission on Jobs and Economic Development

In an attempt to respond to the recommendations of these reports, the UM College of Engineering has developed a strategy for assisting in statewide economic development activities. This strategy is reviewed in this Appendix.

Michigan's Path to Prosperity

As pointed out by the Ross Report, a state becomes prosperous in one way only: by increasing the value of the goods and services that industries in its economic base sell outside the state. While industries such as retail trade and medical services are among the fastest growing, they do not contribute to the economic base but rather simply shift resources internally from one economic sector to another. Rather, the vast majority (90%) of Michigan's economic base lies in durable goods manufacturing. In a sense, manufacturing industry is and will remain the real strength of Michigan's "economic engine".

By combining the state's largely unskilled and semi-skilled workforce with substantial amounts of capital and technology, Michigan has made its workers the most productive and best paid in the world. However today the facilities and technology employed by unskilled labor in high volume standardized production can be purchased by manufacturers anywhere.

Hence Michigan industry must replace the standardized, routine, low-skill, mass production of familiar products, in which we can no longer complete unless we dramatically lower wage rates, with competitive new products and processes that require skilled labor. We must shift our state's economic base toward products and processes that depend on the one part of the production system that cannot be readily transferred to competing regions: human skills. These skills include those of production workers, managers, technologists, and researchers. Production processes that rely on human skills must remain where the skilled people are.

Economic prosperity for Michigan lies not in tearing down the state's old industrial base for a different kind of economy, but in helping that base make the changes necessary to compete in a new economic environment. Indeed, because of its existing agglomeration of durable goods manufacturing firms, skills, and infrastructure, Michigan possesses an advantage in the competition to become a leading world center of durable goods complex manufacturing.

Michigan must become America's factory of the future. And it must become a world center for the export of the new industrial technologies and manufacturing machinery that will form the basis of the factory of the future. In Michigan's emergence as the center of complex manufacturing, new technology will not a separate industrial sector; it will be at the heart of every industrial sector.

Our ability to innovate -- to generate and to executive new economic ideas -- must become our principal economic advantage. Only in this way can we be competitive with other regions and nations and productive enough to earn the income required for a rising standard of living. In this sense, innovation will be the energy that drives change in our state's economy.

To position Michigan as the nation's source of emerging industrial technology, we must move rapidly along three fronts:

- To enhance the growth of research and development in Michigan.
- To accelerate the transfer of technology into Michigan industry.
- To develop a strong coalition within Michigan among government, industry, labor, and universities to create a "venture culture" in Michigan.

The Importance of the UM College of Engineering

Experience in other regions suggests that Michigan's success in achieving this rebirth in its industrial base and competing effectively with other states and nations will depend on its ability to build and sustain a world-class engineering school. Such schools play a vital role in economic development since they provide the intellectual creativity fundamental to technological innovation and the talented, broadly-educated engineers capable of understanding and implementing this technology.

Furthermore, when coupled with appropriate technology-transfer mechanisms, there is little doubt that world-class engineering schools at the cutting edge of research and development can have a major impact on both technological innovation and implementation in the private sector. They provide, through their faculty, students, and graduates, the mechanism for transferring research from the campus into the private sector for commercial exploitation. Finally, such schools are usually a key factor in attracting the "risk capital" represented by massive federal R&D contracts.

Experience has also shown that only those engineering schools capable of clearly ranking among the nation's leaders are able to have a major impact on economic development. Only such world-class programs are capable of attracting the outstanding faculty, the talented students, and the massive resources necessary to achieve the required level of excellence.

For this reason, each of the major studies has stressed the importance of the UM College of Engineering in determining the future economic prosperity of our state:

1. The Ross Report has called for special emphasis on the UM College of Engineering:

   "To ensure the lead position in the development of manufacturing production processes, Michigan must invest heavily in centers of applied research in industrial technology, with special emphasis on developing the University of Michigan College of Engineering as a world leader in this field."

2. The Governor's Commission on the Future of Higher Education has stressed:

   "The existence of high-quality engineering programs is critical to Michigan's economic future. The Commission recommends that state funds be focused on the few high-quality engineering programs consistent with institutional roles and missions."

3. The Governor's Commission on Entrepreneurship and Small Business Development has singled out UM Engineering as a key factor in enhancing the growth of R&D in Michigan, accelerating the transfer of this technology into Michigan industry, and developing a "venture culture" in our state.

4. The Governor's Commission on Jobs and Economic Development has stressed the importance of leading engineering schools on the future of industry in our state.

There are several reasons for this focused attention on the UM College of Engineering as a major factor in Michigan's future: The College is a unique resource in this state. It alone among Michigan's institutions of higher education is within striking distance of achieving the degree of national leadership in engineering education and research necessary for major long term economic development.

The College is presently ranked 5th in reputation among the nation's leading engineering schools. It has been identified as a national center of excellence in technologies of critical importance to Michigan, including complex manufacturing technology, machine intelligence, microelectronics and optical devices, industrial engineering, computer engineering, and materials engineering. Furthermore, the 6,000 students enrolled by the College presently rank among the top 2% of Michigan's high school graduates and hence represent perhaps this state's most valuable source of "intellectual capital".

Coupled with this strong emphasis has been an increased recognition that prompt action is necessary to restore an adequate level of State support to allow the UM College of Engineering to play the role it must in establishing Michigan as the leader in emerging industrial technology. Each of these studies has called for increased commitments on the part of State government to provide the UM College of Engineering with the resources necessary to remain competitive with leading public and private engineering schools.

While such support will be a necessary prerequisite if the College is to play the critical role expected of it, there are also other steps which must be taken. The UM College of Engineering believes it has a major responsibility to respond to the needs of Michigan and its industry:

- Through the attraction of outstanding engineers and scientists and the establishment of national research centers of excellence capable of technological innovation.

- Through the transfer of this technology to Michigan industry through its graduates, continuing engineering education, research partnerships, and the formation of spinoff companies.

- Through direct participation in economic development by attracting companies and national R&D centers to Michigan and encouraging its faculty and graduates to spin off new companies.

A Strategy for Statewide Economic Development

The UM College of Engineering probably has its largest impact on statewide economic development through the over 1.800 engineers it graduates each year -- roughly 70% of whom accept positions in the Great Lakes area -- and the research achievements of its faculty and staff. However in recent years, UM Engineering has gone beyond these traditional mechanisms to initiate a number of new programs aimed at regional economic development. The College has developed its strategy in close cooperation with leaders of state government, industry, and business.

The basic strategy can be grouped into three areas:

Technological Innovation:

- The attraction of outstanding engineers and scientists to Michigan
- The establishment of national research "centers of excellence"

Technology Transfer:

- Traditional mechanisms (graduates, consulting, publishing)
- Research partnerships with industry
- Continuing engineering education
- Formation of spinoff companies
- Industrial consortia

Job Creation:

- Formation of spinoff companies
- Attraction of new companies to Michigan
- Attraction of major national R&D centers

We will consider each component of this strategy in turn.

Technological Innovation:

As noted by the Ross Report, "innovation is the energy that drives change in a state economy". It has also been noted that most of the significant technological innovations that stimulated industrial growth in other parts of the country originated in leading engineering schools. Hence, it is reasonable to expect that the UM College of Engineering will play (and has played) a similar role in stimulating technological innovation in Michigan.

To be a world leader in emerging industrial technology, Michigan must attract engineers and scientists of extraordinary ability and creativity. The UM College of engineering is one of the few institutions in the nation with the proven ability to attract such people.

For example, the 6,000 students presently enrolled in the College probably represents the largest concentration of students with exceptional abilities in science and mathematics of any institution in the United States. Furthermore, over the past three years the College has recruited 70 new engineering faculty from the finest institutions in this nation (Stanford, MIT, Caltech, ...).

In recent years the College has been able to build several programs which are now clearly identified as national research centers of excellence:

Center for Research on Integrated Manufacturing (CRIM)
Industrial Technology Institute (ITI)
Air Force Center of Excellence in Robotics
Computer-Aided Engineering Network
Center for Ergonomics
SRC Center of Excellence in Semiconductor Manufacturing

Additional major research centers under development include:

Center for Applied Optics
Materials Research Laboratory
Solid-State Electronics Laboratory
Center for Scientific Computation
Artificial Intelligence Institute
Machine Intelligence Center
Applied Physics Program

Technology Transfer:

Traditionally, leading engineering schools such as the UM College of Engineering have transferred technology to the private sector in the following ways:

- Placement of graduates in Michigan industry
- Co-operative engineering education
- Continuing engineering education for Michigan industry
- Publication of research results in the open literature
- Faculty/industry exchange programs
- Faculty and staff consultation with industry
- Special research projects conducted for industry

However, in recent years the College has gone beyond these traditional mechanisms to develop new ways to transfer technology. One of the most important mechanisms involves Industrial Affiliates Programs in which 10 to 20 companies will work with the College in areas of specific technological interest. Ongoing Industrial Affiliates Programs include:

- Solid-State Electronics
- Robotics
- Ergonomics
- Flow Reaction and Porous Media

- o Colloidal and Surface Phenomena
- o Machine-Tool Wear and Sensing
- o Information Systems Engineering
- o Computer-Aided Manufacturing
- o Construction Engineering and Management
- o Computer-Enhanced Productivity (EPIC)

The College has pioneered in the development of a more sophisticated and sustained type of relationship known as the Industrial Research Partnership. In these partnerships, the College works closely on common research problems with key companies. The College forms teams of PhD students led by faculty which then work side by side with industrial engineers and scientists (both in company facilities and on campus). Such partnerships have already yielded dramatic leaps forward in critical areas of technology. Existing research partnerships have been formed with the following companies:

- o General Motors: "factory of the future"
- o Ford: ergonomics, electronics, design
- o IBM: supercomputers and robotics
- o Intel: computer science
- o Semiconductor Research Corporation: automation
- o General Electric: computer-aided design
- o General Dynamics: computing networks

Other partnerships presently under negotiation include:

- o Chrysler: computer-integrated manufacturing
- o Dow: chemical process control
- o Bechtel: CAD in large-scale construction

<u>Job Creation</u>:

The UM College of Engineering is also involved in a number of activities aimed at direct job creation. One of the most important such mechanisms is through the formation of new "spinoff" companies by faculty, staff, and students. This has always been an active area, as evidenced by the 77 companies formed by the College and its affiliated research laboratories over the past two decades. However, strong steps are now being taken to encourage and facilitate this activity, and the rate of spinoffs is increasing rapidly.

There has also been considerable activity directed toward attracting industry to Michigan. Through close coordination with state and local government, the College has used its extensive industrial contacts to identify and interact with prospective companies. During the course of a typical academic year, faculty and staff of the College will conduct 50 to 60 day-long briefings both on campus and at industrial sites with the intent of stressing the desirability of locating new installations in Michigan. The College has also been an important partner in efforts to develop several research parks in the southeastern Michigan area.

Finally, the UM College of Engineering has frequently played a key role in attempts to attract major national R&D centers to Michigan. For example, the College provided the principal technical component of the State's proposal for siting the Microelectronics and Computer Corporation. It has taken the lead in efforts to attract the DOD Software Engineering Institute and the NSF National Supercomputer Center. Similar efforts are now underway to compete for the following centers:

- Air Force Artificial Intelligence Institute
- National Knowledge Engineering Center
- NSF Materials Research Laboratory
- DOD Strategic Defense Initiative
- National Laser Institute
- NSF Engineering Research Center

Conclusions

There seems little doubt that the UM College of Engineering represents a valuable resource to Michigan. Its role will become increasingly important as Michigan strives to diversify and strengthen its economic base with technology-based industry. In this sense, the UM College of Engineering provides state government with both a vehicle and an extraordinary opportunity for investing in the long-term economic health of our state.

APPENDIX C

EXAMPLES OF ACTIVITIES OF THE UM COLLEGE OF ENGINEERING RELATED TO ECONOMIC DEVELOPMENT

1. In 1981 the College established the Center for Research on Integrated Manufacturing to conduct research and instruction in areas concerned with the computer-based automation of the functions of industrial production, ranging from product design to manufacturing to management, sales, service, and upgrading -- all of the activities of the so-called "factory of the future". As the Ross Report has noted, it is just such complex manufacturing that will be the key to Michigan's long-term economic prosperity. The Center currently involves the efforts of 45 faculty and 100 graduate students from 6 academic departments. In less than three years, the Center has received international recognition as one of the leading manufacturing research programs in the nation. It has built a sustained level of funding from industrial and federal sources of roughly $6 million per year.

2. The College played a key role in the development of the Industrial Technology Institute of Michigan. This Institute will be come a world-class center for research and development in a variety of areas related to manufacturing, ranging from automation and manufacturing processes to technology transfer and the social implications of industrial technology. The Institute is currently housed in College facilities and building its initial programs with the assistance of College staff. Within a short time the Institute expects to employ roughly 200 staff and be engaged in a broad spectrum of basic and applied research and development in manufacturing.

3. In parallel with these major thrusts into industrial technology and manufacturing engineering, UM Engineering has begun an exciting new program in "white collar" or "professional" productivity, the EPIC Project (Enhanced Productivity through Integrated Computer Workstations). In collaboration with several Michigan companies, the College is working to apply modern computer and communications technology to develop a prototype computer network of tomorrow, the Computer Aided Engineering Network, that will support industry and business. Major computer companies such as IBM, Apollo, Apple, AT&T, EDS, and General Electric are active participants in assisting in the development of this system.

4. The College of Engineering conducts the leading program in the nation in occupational health and safety through its Center for Ergonomics. Recently, the Center has played a key role in analyzing and restructuring the workplace environment of the factories of one of Michigan's leading companies, in order to address the concerns both of labor and management. Of particular concern has been the development of an effective "man-machine interface" between workers and automated machines.

5. In 1984 the College began construction of the Laboratory of Electrical Engineering and Computer Science. Concurrent with this project, the College has consolidated its programs in electrical engineering, systems engineering, and computer science and engineering into one of the largest and most comprehensive Departments of Electrical Engineering and Computer Science in the nation, with almost 100 faculty and 1,800 students. Moreover, during the past two years the College has developed what is now regarded as the nation's most sophisticated university computing environment. These factors have provided Michigan with world-wide recognition for its programs in electrical engineering, computer science, and telecommunications techology -- areas of critical importance to Michigan industry.

6. In recognition of its combined strengths is solid-state electronics and industrial automation, the American electronics industry recently selected the UM College of Engineering (along with Stanford and the North Carolina Research Triangle) as the cornerstone of a major new research effort concerned with developing the technology of the microelectronics factory of the future. Since the automobile industry will be both the largest consumer and manufacturer of electronic components, this research project has an extraordinary importance for future industrial growth in the state.

7. The College has recently attracted several of the leading materials scientists in the nation to build a world-class research laboratory in advanced materials research. Eight new faculty will be added in this important area. The College is now seeking a $6 million grant from the National Science Foundation to establish a major Materials Research Laboratory in Michigan.

8. The College has been the driving force behind the University's efforts to attract a major federally-sponsored supercomputer center to Michigan. Associated with the center will be a Center for Scientific Computation which will attract many of the leading scientists and engineers in the world to our State.

9. The College is building on its traditional strength in applied optics to establish a new Center for Applied Optics. Research areas for the Center include optical diagnostics, high-powered lasers, opthmological measurements, laser spectroscopy, holography, optical data processing, guided optics, coherent optical measurement techniques, and nonlinear optics. Of particular interest will be a major new program in optoelectronics -- optics on a chip. Since many believe that this technology will eventually replace microelectronics, the development of one of this nation's leading programs in this area could well trigger a Silicon Valley (more precisely, a "Gallium Arsenide" Valley) phenomenon in the southeastern Michigan area.

10. Research and instruction in artificial intelligence has been a part of many departments at Michigan. The recent creation of the Department of Electrical Engineering and Computer Science has brought together the majority of researchers in this area. The College is committed to

building a strong applied research program in artificial intelligence with special emphasis on industrial applications. Working closely with major companies such as Electronic Data Systems (recently acquired by General Motors), the College intends to build a national Institute in Knowledge Engineering, the application of artificial intelligence to manufacturing processes.

11. For many years the College has conducted Industrial Affiliates programs in which companies collaborate in a variety of technical areas of mutual interest. At present there are ten such programs in areas such as Robotics, Solid State Electronics, Machine Tool Wear, CAD/CAM, Catalysis and Surface Science. However, UM Engineering has recently negotiated several more extensive interactions, Industrial Research Partnerships, with key companies such as General Motors, IBM, and General Dynamics in which the College places faculty-graduate student teams into their facilities to identify and develop joint research projects, and then these teams return to campus, along with their industrial colleagues, to continue the research.

12. The College has taken very seriously its obligations to transfer the fruits of its research activities into the private sector to stimulate economic growth and job creation. Through a major restructuring of internal prolicies, the College has sought to encourage faculty and students to spin off research developments into the private sector. During the past year along, 7 new companies have been started by faculty of the College bringing the total number started by College faculty, staff, and affiliated laboratories to 85 (see Appendix C).

13. Furthermore, the College has worked with the University to found the Michigan Research Corporation, an independent corporation, with the mission of identifying intellectual properties developed on campus and providing the guidance and resources necessary to bring these to commercial application. The College also works quite closely with a number of leading venture capital firms.

14. The College has taken steps to expand its delivery of instruction in engineering to industry through a variety of mechanisms, including its Instructional Television Network, tutored-videotape instruction, and engineering short courses and conferences held both oncampus and at widely-scattered industrial sites. It is also participating with industry through co-operative education programs in a variety of fields.

15. The College has cooperated closely with state and local government in a variety of economic development activities. For example, the College was a founding member of the Michigan Technology Council. Furthermore, it has participated with the Governor's Office in efforts to attract new companies and national R&D Centers to Michigan.

APPENDIX D

SPINOFF COMPANIES ESTABLISHED BY
UM ENGINEERING FACULTY AND STAFF

Applied Dynamics, Inc.	(Howe)
Applied Theory, Inc.	(Cole)
Arktronics	(students)
Automated Analysis Corp.	(Anderson)
CFR Inc.	(Hilliard)
Coastal Dynamics Inc.	(Meadows)
Conductron	(Siegel)
Electrocon International	(Enns)
Environmental Dynamics Inc.	(Cole, Weber)
ESZ Associates Inc.	(Edlund, Shure, Zweifel)
Explosion Research Corp.	(Kauffman)
ISDOS Inc.	(Teichroew)
Limno-Tech Inc.	(Canale)
Jodon Inc.	(Gillespie)
Michigan Automotive Research Corp.	(Cole)
Machine Vision International	(Sternberg)
Materials Technology Corp.	(Felbeck, Jones, Bolt)
Mechanical Dynamics Inc.	(Chace)
Medicus Inc.	(Jelinek)
Project Management Assoc.	(Ponce De Leon)
QED Environmental Systems	(Weber)
Raycon, Inc.	(Check, Rupert)
Solarcon, Inc.	(Clark)
Starpak Energy Systems, Inc.	(Clark)
Stoll, Evans, Woods, Consultants	(Woods)
TDR Inc.	(Felbeck)
Transidyne General	(Diamond)
Traverse Group	(Armstrong)
VAI	(Vorus)
Vector Research	(Bonder)

SPINOFF COMPANIES ESTABLISHED BY
UM ENGINEERING AFFILIATED LABORATORIES

(Willow Run, ERIM, Space Physics Research Labs, Radiation Lab...)

Argo Science, Inc.	1976
Ann Arbor Computer Corp.	1972
Applied Intelligent Systems	1982
Arono Pemex	1969
Bendix Aerospace Division	1961
CFC, Inc.	1971
Conductron	1960
Control Data Corp.	1958
Crystal Optics Research, Inc.	1963
Cytosystems Corp.	1982
Daedalus Enterprises	1969
Data Max	1967
Data Products	1960
Data Systems, Inc.	1961
DeKalb, Inc., Sensors Div.	1974
First Ann Arbor Corp.	1967
Geospectra Corp.	1974
Harris Electro-Optics Center	1969
Hearing & Noise Assoc.	1979
Hewlett-Packard, Data Systems Div.	1964
Holly Carburetor-Rochester Div.	1957
Intelldata, Inc.	1959
Irwin Industries International	1979
Jervis Webb, Inc., AA Comp. Div.	1973
KMS Corporation	1969
KMS Fusion	1971
Kaiser Optical Systems, Inc.	1980
Laser Systems, Inc.	1967
Lear Siegler, Laser Systems Div.	1965
Machine Vision International	1983
Manufacturing Data Systems, Inc.	1962
McDonnell Douglas, Conductron Div.	1967
Michigan Computers and Instru.	1983
Nichols Research Corp.	1978
Northern Telecom, Sycor Div.	1978
Olivetti, Inc. - Irwin	1982
OptiMetrics, Inc.	1979
Photon Equipment	1957
Radiation, Inc., Adv. Optics Center	1968
Ritt Labs	1962
Sarns, Inc.	1962
Science Applications Inc. (AA Div.)	1972
Sensor Dynamics	1964
Sensors, Inc.	1969

Sonovision	1971
Strand Consultant	1965
Strand Engineering, Inc.	1960
Sycor, Inc.	1967
Synthetic Vision Systems, Inc.	1983
Trion Institute	1960
Union Carbide, Data Systems Div.	1962
Veda Corporation (Ann Arbor)	1964

UM COLLEGE OF ENGINEERING

FACT SUMMARY

REPUTATION:

- Generally ranked 5th nationally in overall quality.
- 18 of its degree programs are ranked in the top ten.
- UM's programs in industrial engineering, aerospace engineering, nuclear engineering, and naval architecture are generally regarded as national leaders.

TRADITION:

- UM has 7th oldest engineering college.
- Ranks 3rd in total number of degrees awarded (50,000).
- Pioneered in introduction of programs: metallurgical engineering (1854), naval architecture (1881), chemical engineering (1901), aeronautical engineering (1916), nuclear engineering (1953), and computer engineering (1965).

CAPACITY:

o Enrollment (1984):	Undergraduates	4,512
	Masters	1,041
	Doctorates	539
	Total	6,092
o Degrees (1984):	B.S.	1,210
	M.S.	584
	Ph.D.	93
	Total	1,887

- Ranks 4th nationally both in enrollment and degrees.

STUDENT QUALITY:

- 3,400 applications for 750 positions.
- Average entering freshman ranked in 98th percentile.
- SATs: 580 verbal, 680 math (1260)
- Entering high school grade point average: 3.8
- 27% of entering freshmen are straight A (4.0) students.

FACULTY CHARACTERISTICS:

- 320 faculty members.
- Over 100 new faculty will have been hired in period 198085.
- 650 research staff.

RESEARCH ACTIVITY:

- $25 million per year in federallysponsored research (plus an additional $12 million in affiliated institutes).
- Research in all areas of science and technology.
- Major new interdisciplinary research efforts: integrated manufacturing, microelectronics, materials processing, biotechnology, ergonomics, space systems instrumentation, applied optics, computer systems and networks, gas dynamics and combustion, supercomputers

RESOURCES:

o Physical Plant:	1,000,000 nsf (15 buildings)
o Equipment Inventory:	$30 million
o Computer Network Inventory:	$20 million
o Operating Budget:	
Tuition Revenue	$25 million
Sponsored R&D	$25 million
Gifts	$10 million
State appropriation	$10 million
Total	$70 million

NARRATIVE DESCRIPTION

The College of Engineering of the University of Michigan has consistently ranked among the leading engineering schools in the nation and the world, whether measured by the quality of its instructional programs, its research accomplishments, or the impact of its graduates. The College's combination of disciplinary breadth and depth of quality across the full spectrum of instruction and reserach make it unusual among the nation's engineering schools. Most surveys rank each of the College's undergraduate and graduate degree programs high among the leading programs in the nation.

The College is one of the few leading engineering schools imbedded in a great univeristy with strengths across all academic and professional disciplines. This has provided it with a unique opportunity to develop new academic programs and applications involving those related fields. It has also provided students of the College with an unparalleled breadth of educational opprotunities and experiences. Graduates of the College are widely known for their strong background in fundamental science and their ability to apply this knowledge in engineering practice. They move easily and rapidly into positions of leadership in industry, government, and academe.

The primary objective of the College for the decade ahead is to continue and to strengthen its position of leadership in engineering education by achieving excellence in education, research, and the pofessional activities of faculty, students, and graduates.

Today over 6,000 students are enrolled in the College's 20 degree programs. Each year it graduates more than 1,800 engineers at the BS, MS, and PhD levels. Ranking third among engineering schools in the total number of degrees awarded, it has more than 50,000 alumni spread throughout the world.

In recent years the College has seen an unprecedented interest on the part of the most outstanding high school graduates to enroll in its programs. For example, in 1984 the average entering freshman ranked in the 98th percentive of his or her high school graduating class. Over 25% of these students had perfect 4.0 grade point averages in high school. The College has seen a similar increase in the demand for admission to its graduate programs (particularly at the PhD level).

The College has long been a leader in the development of new academic programs at the very forefront of technology. It pioneered in the introduction of programs in metallurgical engineering (1854), naval architecture (1881), chemical engineering (1901), aeronautical engineering (1916), nuclear engineering (1953), and computer engineering (1965). This tradition of leadership continues today, as evidenced by the College's thrusts into such new areas as robotics and computer-integrated manufacturing, microelectronics, biotechnology, and advanced materials.

The College has adopted a matrix management structure to coordinate its array of research activities. As such research efforts have demanded a broader, interdisciplinary approach involving the strong interaction of a number of traditional academic disciplines, the College has created numerous research Laboratories, Centers, and Institutes to coordinate these activities. Of particular note are major research organizations such as the Center for Research on Integrated Manufacturing, the Space Physics Research Laboratory, the Center for Ergonomics, the Solid State Electronics Laboratory, the Phoenix Memorial Laboratory, the Computing Research Laboratory, and the Ship Hydrodynamics Laboratory.

In addition, the College has developed numerous mechanisms for interacting more closely with industry. These range from a variety of Industrial Affiliates programs in which a number of companies will sponsor and participate in research in particular areas, to Research Partnerships in which the College will work closely with a particular company to develop a major research relationships involving facultyled teams of PhD students along with scientists and engineers from industry. In addition the College has spawned several research organizations separate from the University such as the Industrial Technology Institute and the Environmental Research Institute of Michigan to better facilitate industrial research. And, of course, the College continues to provide assistance to industry through cooperative engineering education programs, continuing engineering education, and its Instructional Television System.

Finally, the College of Engineering has strongly encouraged its faculty, students, and staff to become involved in the transfer of intellectual properties from the campus into the private sector. Working closely with the University, it has streamlined conflict of interest regulations to facilitate the establishment of spinoff companies. (By way of example, in 1983, faculty and staff of the College started 7 new companies.) It has also worked closely with venture capital groups, financial institutions, and the UM School of Business Administration to stimulate this important activity.

UM COLLEGE OF ENGINEERING

A TRADITION OF EXCELLENCE

SOME PARAMETERS:

- o UM has 7th oldest engineering college.
- o It ranks 3rd in total number of degrees awarded (50,000).
- o Pioneered in introduction of programs: metallurgical engineering (1854), naval architecture (1881), chemical engineering (1901), aeronautical engineering (1916), nuclear engineering (1953), and computer engineering (1965).

SOME FIRSTS OF UM ENGINEERING:

o Metallurgical Engineering	1854
o Naval Architecture	1881
o Chemical Engineering	1901
o Aeronautical Engineering	1916
o Nuclear Engineering	1953
o Computer Engineering	1965

UM COLLEGE OF ENGINEERING

CAPACITY

ENROLLMENTS (1984):

Undergraduates	4,512
Masters	1,041
Doctorates	539
Total	6,092

DEGREE PRODUCTION (1984):

B.S.	1,210
M.S.	584
Ph.D.	93
Total	1,887

ENROLLMENT PATTERNS:

Electrical and Computer Engineering	1,427
Mechanical Engineering	912
Chemical Engineering	445
Aerospace Engineering	443
Civil Engineering	391
Industrial Engineering	382
Computer Science	340

UM COLLEGE OF ENGINEERING

STUDENT CHARACTERISTICS

STUDENT QUALITY:

Selectivity:	3,400 applicants for 750 positions
Percentile Ranking:	98th percentile
SAT Scores:	580 verbal 680 math 1,260 total
High School GPA:	4.0 (27% of class) 3.8 (average) 3.5 (cutoff)
Attrition rate to graduation:	10%

OTHER STUDENT CHARACTERISTICS:

- o 23% women
- o 7% minority (3% black)
- o 74% of undergraduates from Michigan
- o 11% foreigh nationals

UM COLLEGE OF ENGINEERING

NATIONAL RANKINGS

CAPACITY:

o	Enrollment:	Undergraduate:	4th
		Graduate:	4th
o	Degree Production:	B.S.	4th
		M.S.	4th
		Ph.D.	6th
o	Alumni:		3rd
o	Sponsored Research Volume:		7th

QUALITY:

- o Overall Quality: 5th or 6th

- o Program Rankings:

Program	UG	Grad
Atmospheric & Oceanic Sciences		
Aerospace Engineering	2nd	3rd
Chemical Engineering	9th	9th
Civil Engineering	7th	8th
Computer Science & Engineering		
Electrical Engineering	5th	5th
Engineering Science	3rd	
Industrial Engineering	1st	1st
Materials Engineering	3rd	
Mechanical Engineering	4th	5th
Metallurgical Engineering	9th	9th
Naval Architecture	1st	2nd
Nuclear Engineering	1st	2nd

UM COLLEGE OF ENGINEERING

ACADEMIC PROGRAMS

DEPARTMENTS:

Atmospheric and Oceanic Sciences
Aerospace Engineering
Chemical Engineering
Civil Engineering
Electrical Engineering and Computer Science
Industrial and Operations Engineering
Materials and Metallurgical Engineering
Mechanical Engineering and Applied Mechanics
Naval Architecture and Marine Engineering
Nuclear Engineering

DEGREE PROGRAMS:

Aerospace Engineering (BS, MS, PhD)
Applied Mechanics (BS, MS, PhD)
Applied Physics (MS, PhD)
Atmospheric Sciences (BS, MS, PhD)
Bioengineering (MS, PhD)
Chemical Engineering (BS, MS, PhD)
Civil Engineering (BS, MS, PhD)
Construction Engineering (MS, PhD)
Computer Engineering (BS, MS, PhD)
Computer Science (BS, MS, PhD)
Electrical Engineering (BS, MS, PhD)
Engineering Physics (BS)
Industrial and Operations Engineering (BS, MS, PhD)
Manufacturing Engineering (MS)
Marine Engineering (BS, MS, PhD)
Materials Science and Engineering (BS, MS, PhD)
Mechanical Engineering (BS, MS, PhD)
Metallurgical Engineering (BS, MS, PhD)
Naval Architecture (BS, MS)
Nuclear Engineering (BS, MS, PhD)
Oceanic Sciences (BS, MS, PhD)

UM COLLEGE OF ENGINEERING

RESEARCH LABORATORIES, CENTERS, AND INSTITUTES

MAJOR RESEARCH UNITS:

- Automotive Laboratory
- Center for Catalysis and Surface Science*
- Center for Ergonomics
- Center for Research on Integrated Manufacturing
  - Robotics Systems Division
  - Integrated Design and Manufacturing Division
  - Manufacturing Systems Division
- Computer-Aided Engineering Network
- Computing Research Laboratory
- Gas Dynamics Laboratory
- Great Lakes Research and Marine Waters Institute*
- Laser-Plasma Interaction Laboratory
- Macromolecular Research Center*
- Rehabilitation Engineering Center
- Phoenix Memorial Laboratory (Ford Nuclear Reactor)*
- Solid State Electronics Laboratory
- Space Physics Research Laboratory
- Ship Hydrodynamics Laboratory
- Transportation Research Institute*
- Water Resources Laboratory

RESEARCH UNITS UNDER DEVELOPMENT:

- Center for Applied Optics
- Center for Scientific Computation*
- Materials Processing Research Institute*

*Intercollege activity

UM COLLEGE OF ENGINEERING

RESEARCH AREAS OF MAJOR THRUST

TRADITION OF NATIONAL LEADERSHIP:

Aerospace Engineering
Applied Optics
Atmospheric Sciences
Gas Dynamics
Image Processing
Industrial Engineering (ergonomics, operations research)
Naval Architecture
Nuclear Engineering
Remote Sensing
Thermal and Fluid Sciences
Solid State Electronics (sensors, microwaves)

MISSION FOR NATIONAL LEADERSHIP:

Integrated Manufacturing
Materials Processing Technology
Biotechnology
Computer Science and Engineering

POTENTIAL FOR NATIONAL LEADERSHIP:

Applied Mechanics (micromechanics)
Advanced Scientific Computation (supercomputers)
Construction Engineering
Electronic Materials
Modern Optics (optoelectronics, nonlinear optics)
Polymer Process Engineering

UM COLLEGE OF ENGINEERING

KEY INTERDISCIPLINARY THRUST AREAS

Engineering and LSA:

Computer Science and Engineering (CCS + ECE --> EECS)
Applied Physics (Physics, Nuclear, ECE, MME)
Materials Research (Physics, Chemistry, MME, ChE)
Numerical Analysis and Scientific Computation (Eng, Math)
Earth and Planetary Sciences (A&OS, Geo Sci)
Biotechnology (Bio Sci, Chem, ChE, ECE)

Engineering and Medicine:

Biotechnology (Med, ChE, ECE)
Image Processing (Med, ECE, Nuclear, MEAM)
Biomechanics (Med, MEAM)

Other Interactions:

Ergonomics (Eng, Pub Health, Med)
Biochemistry (Eng, Phar, Med)
Computer Networks (Eng, LSA, Bus Ad, Med)
Transportation (Eng, Pub Health, UMTRI)
Water Sciences (Eng, LSA, Pub Health, Nat Res, GRMLK)

APPENDIX A. PRODUCT DESIGN

A.1. OBJECTIVES

The overall objective is to study the appropriate transition from design "art" to design "science," so that human creativity can be most effectively focused. The study must focus both on the human designer as the creator of new products and on the tools available to realize his creations in a rational way. It must also address the issue of how a product should be made, not just what it should do. Thus the specific objectives, varying from emphasis on the designer to emphasis on the design tools, are:

a. To gain insights into the designer's mental process of creation/synthesis in the context of modern computer-based tools.

b. To analyze the obstacles to design automation and to define the specific needs for streamlining the design process.

c. To study explicitly how manufacturing considerations can be properly included in the early stages of product development.

d. To extend optimization principles beyond product performance to include manufacturing and other criteria.

e. To contribute to integration of design/analysis methods, interactive computer graphics, and optimization techniques, using engineering workstations.

A.2. MOTIVATION AND PROBLEM PERSPECTIVE

A.2.1. Design Methodology of the Future

Designs today are complex products of human intelligence. However, much of that complexity can be reduced to operations that can be delegated to computers for processing, hence the emergence of CAD/CAM, expert systems ideas, and discussions of "design science" (Simon, 1981). Whether the design process can indeed become a scientific process is worthy of (at least) philosophical discussion, but for practical purposes, in the next few decades, part of design will remain an intuitive human art. Aspects of the process will continue to resist effective mathematical description, both because of the complexity of the required information and because of the often observed lack of total rationality in the decisions that lead to a particular product. The process of synthesis will be mostly performed by humans, and it is desirable to investigate what computers can and should do best to assist humans in this process.

In agreement with the overall ERC objectives, it is considered critical for the future to include design procedures as part of the total production process. It has been argued that in the past design dictated manufacturing, and that now we must gain competitiveness by having manufacturing-dictated design. Obviously, replacing one extreme with another is undesirable in the long run. The need is to find ways to integrate the two, much as a craftsman in years past was able to produce well, because of his fairly complete knowledge both of functional needs and production tools.

The specific tasks of automation and integration can be discussed more easily if a traditional definition of terms is agreed upon: design includes all technical activities from product conception to certified dataset (formerly drawings) release; manufacturing includes all technical activities for making the product.

A.2.2. Optimal Design

In traditional product development, a new product was eventually "optimized" through repeated cycling among analysis, synthesis, and manufacturing. This involved many individuals and a long time. Today a partial integration of analysis and synthesis has been achieved through mathematical optimization.

Optimal engineering design today is primarily the solution of nonlinear programming (NLP) problems, where the mathematical model represents the product. Typically, one or more desirable characteristics are selected as the objective(s) in the model while functional, performance, and geometric requirements are included in the form of equality and inequality constraints. The problem functions (e.g., objectives, constraints) may be explicitly stated or may be defined implicitly through subroutines that themselves represent complex calculations, such as solutions of systems of differential equations. Even better approximations to reality require accounting for several discrete variables, non-differentiable functions, and possibly disjoint feasible domains.

It is clear from the NLP viewpoint that optimal design problems are, in general, very difficult to solve; however, good engineering understanding and proper use of general purpose NLP codes have produced marked success (e.g., Lev, 1981) with current industrial applications in the aerospace, automotive, and marine structures industries (see NASA-Langley Symposium, 1984). Current progress in NLP software promises that the solution of classical, i.e., continuously differentiable, NLP problems will be accessible with a reasonable degree of confidence (NATO Advanced Study Institute, 1984). In mechanical design much progress has been achieved (e.g., Mayne and Ragsdell, 1981, NATO-NSF-ARO, 1983), but it has not yet been passed on to industry to a desired degree. There are several reasons:

a. Many engineers are rather conservative in using new technology and are not educated sufficiently in systems sciences.
b. Mathematical structures of machine design problems are very complex and varied and thus not well suited for treatment with currently available modeling methods.

c. The configuration of mechanical designs, i.e., the functional arrangement of components or the topology of each component, is generally more complex than defining the geometric dimensioning of a prescribed shape. Most optimal design today does simple proportioning of a base configuration. There are some exceptions, particularly in shape optimization (Taylor and Olhoff, 1983; Kikuchi et al., 1984; Diaz et al., 1983).

d. Optimal design models usually include only function and geometric constraints but no manufacturing considerations. These are now handled in a rather primitive way: minimizing an objective that represents costs proportional to volume and/or including simple upper/lower bound constraints on design variables to limit them, for example, in thickness "for manufacturing reasons." An example of introducing this type of consideration in the design phase is setting goals for redesign that include frequency and mode shape constraints (e.g., Hoff et al., 1984). This is not sufficient for realistic design; more creativity is needed to include considerations beyond thickness control.

In spite of these difficulties, the optimization context is considered here as a very powerful and promising integration mechanism. Substantial results can be expected from the integration of optimization techniques, analysis methods, graphics, and experimental verification. Also, traditional NLP models and techniques may need to be merged or modified with artificial intelligence concepts (Papalambros and Azarm, 1984, Papalambros and Li, 1984; Jakiela et al., 1984).

A.2.3. Some Obstacles to Automation/Integration

In spite of remarkable successes, there are still several obstacles that bear on the research plan.

Technical: Technical inadequacies of computer hardware and software are continuing obstacles to wider use. For example, in the design process the computer-based product model, most commonly conceived and defined by one of several turn-key CAD/CAM systems, makes excellent drawings and performs a few other design, analysis, and manufacturing tasks moderately well, but is far from being a universal tool in the centralized database. For example, in the structural analysis area, where compatibility with the CAD geometry is most complete, separate geometric models for finite elements method (FEM) analysis have had to be developed with limited compatibility with the CAD models. In turn, these models have limited capability to produce drawings and serve other functions. Furthermore, neither model serves well the needs in other analysis areas, such as thermal, fluid, etc. A number of firms are hard at work to develop new geometric modelers, usually based upon solid modeling concepts, which may overcome the deficiencies of earlier systems. Some are beginning to appear on the market.

Nevertheless, it will be some time before the gaps close, and these modelers meet the needs of the variety of users found in the various phases of product development. Similar examples can be cited in other parts of the design/manufacturing process.

Economic: Where technical deficiencies are not severely limiting, the economic factors may be. For example, current full-featured CAD/CAM systems are expensive to buy, maintain, and operate. These costs often make them unsuitable for any but a few full-time trained operators whose primary product is drawings and layouts. The systems are difficult to learn to use and thus frequently unsuitable for the part-time or intermittent user found in analysis and preliminary design groups. Instead of contributing to the demise of the draftsman, they are ensuring his survival in the reincarnated form of the CAD system operator. A new generation of CAD/CAM systems that combine low cost with ease of use and functionality are eagerly awaited. Fortunately, new hardware in the form of workstations based upon distributed computing will soon lower the cost of hardware and make the development of better software inevitable. Another economic factor is the very large investment in traditional ways of doing things. Under the pressure of heavy work loads, it is not always economically feasible to shift from a known way of doing things to a new way, even when it promises to be more efficient.

Educational: These problems include a middle management which, in many instances, understands neither the concepts of automation and integration nor the steps necessary to carry it out, and a work force resistant to new job classifications and assignments and to learning the necessary skills for the new work environment. Furthermore, new ways of engineering require new ways of doing engineering education; however, for the most part the system is locked into traditional ways of organizing and delivering education. Outmoded courses, curricula, laboratories, and faculty must be updated or replaced. Teaching the middle-aged practicing engineers new skills is a prime concern in industry. For example, most in the current engineering work force were educated in an era (the last three decades) in which graphics was not emphasized in the curricula; consequently, they are not in position to evaluate the potential benefits of the concepts and procedures of computer-aided graphics and CAD systems.

Personal and Human: Traditional attitudes may be effective deterrents to new technology adoption. For example, product engineers often consider themselves the elite engineering workforce (a view not necessarily shared by management), while detailed design and manufacturing are often considered a lower level of engineering endeavor. Furthermore, ergonomic issues have hardly been addressed. For example, there are human factors questions in the design of workstations, the design of workspace (Chaffin and Evans, 1984), and even in software design.

A.2.4. The Role of the University

It is important that the contribution of the College to the solution of problems of this kind be directed to things it can do best and to research activities not being duplicated elsewhere. Several firms, both software developers and users, are working to remove many of the technical and economic deficiencies cited above and to overcome other problems. Two major initiatives by the Federal government, the IPAD and ICAM efforts, are also making major contributions. The universities should not compete with these efforts but should contribute to fundamental developments in basic research. Three major features of the research program proposed here may distinguish it: (1) Current research to improve system integration quite often accepts a fragmented design process as given and attempts to develop tools that bridge between the fragmented parts; in contrast, we propose to streamline a unified concept of design and build integration around this concept. (2) Optimization principles reaching beyond the usual product performance criteria to include manufacturing will be central to the research. (3) Most current research is aimed primarily at the technical feasibility of integration, secondarily at economic feasibility, and only cursorily at other factors; in contrast, we propose to give major consideration to the personal, educational, and human factors as well as the technical and economic factors in all the research.

A.3. RESEARCH PLAN

We propose the following research as a natural extension of current activities in the College:

a. Software integration (graphics, analysis, optimization) via personal engineering workstations. Applications software in stress analysis, dynamic analysis, thermal analysis, etc., would be interfaced with general NLP codes for routine use in design problems.

b. Modeling and solution of optimal design problems that include both product performance and manufacturability tradeoffs. Collaboration with the groups in cell and factory-level production to develop improved models of the manufacturing requirements that can be used in the product design phase. The design optimization procedures would be fine-tuned through data collected in the prototype manufacturing testbed.

c. Employment of artificial intelligence techniques in the context of design process. After the first two or three years, we expect to demonstrate the feasibility of expert optimization principles and convert analysis tools into synthesis tools that can be used for conceptual design (Jakiela et al., 1984).

The research means to facilitate these activities will be the establishment of a Design Laboratory and a Multidisciplinary Optimization Group.

A.3.1. The Design Laboratory

The laboratory will use an empirical approach to achieving the first three objectives in Section A.1, namely, gain insight into the design process, analyze and overcome obstacles to integration, and include explicitly manufacturing considerations in the design process. The laboratory functions will be as follows:

(a) Work with industry to organize an interdisciplinary research team possessing expertise in such areas as:

    i. Mechanical engineering systems
    ii. Manufacturing/materials processes
    iii. Microprocessors/control systems
    iv. Artificial intelligence, expert systems
    v. Man/machine systems; ergonomics
    vi. Educational/organization psychology
    vii. Industrial design

    During the first few months, the team will develop a common research methodology and apply it in the laboratory. The development of the research methodology and its initial application in the on-campus laboratory is expected in the first year. Special attention will be given to how efficiently and accurately information flows during the design process and how knowledge is acquired, stored, and recalled.

(b) In the on-campus Design Laboratory, a group of students will be assigned a team project, selected from an industrial source, which would require developing the product concept and carrying out all the design activities, including the construction of a prototype, with a final design review by students, faculty, and industrial sponsors. Each project will be taken through the entire cycle from need-definition through hardware construction to need-satisfaction.

    The objective here is two-fold. From the educational point of view, the students will experience the practice of design and learn the use of modern design tools in a realistic yet guided environment. From the research point of view, the students and their activities will be the subject of close observation. Their activities will provide the means for discovering and/or defining more specific research goals. Some typical problem areas in design integration may be: (1) decision-making by a single individual based upon interactions with a computer rather than individuals, (2) real impediments to the integration — is it the hardware, software, human, or a combination, (3) computer aids that are natural and creativity-reinforcing, and (4) conversion of specific analysis tools to synthesis aids. In short, the researchers will take a close look at the use of new technology and develop plans to overcome obstacles in the process of providing a real integrated design experience.

After the trial run with a group of students in the later part of the first year of the project, the research will continue with two groups of students in subsequent years — one group in the Fall term and another in the Winter term. Some students from the previous class will carry over to the subsequent class to provide additional continuity to that provided by the faculty. Thus, results obtained by the end of the second year of the project will include three separate cycles, each building upon the preceding ones.

(c) Concurrently, a formal relationship will be established with a design group in an industrial setting. A design project team with composition and goals similar to those of the student teams will be monitored in a company location, working under "real" as distinct from "school" conditions. One or more members of the industrial-based design team will participate on a regular basis, i.e., one or two days a week, with the Design Laboratory staff.

(d) The results obtained from the laboratory by the end of two years will be used to refine the experience and practice in the on-campus laboratory during the third year. A substantial flow of useful information and practices back to the industrial setting is expected during the fourth year. The project will have proved itself by this time, and the fifth year will be used either to refine the process or to move out in new directions. It is not yet possible to project in any detail what useful research will need to be done beyond five years.

Two comments should be made about the laboratory. First, the explicit areas of investigation are loosely defined intentionally because the laboratory itself is considered as the vehicle for a more proper and stricter definition of the research problems beyond the first year. Second, the parallel industrial group will not be involved in prime design work so that it would not be subjected to production deadline pressures. However, success with non-prime projects may lead to prime design work in the fifth year and beyond.

A.3.2. Multidisciplinary Optimization Group

This group will use a rigorous analytical approach toward achieving the last two objectives stated in Section A.1., namely, software integration and incorporation of manufacturing considerations through optimization techniques.

What is proposed initially is to extend optimal structural design research to include optimal manufacturing criteria. Structural design was chosen as the departure point because the structure is the part to be manufactured. In the process of optimal structural design, the shape and material properties of the part are defined. It is the task of manufacturing to cast, forge, machine, bend, etc., that part into its structural shape out of certain materials. Thus, most of the variables appropriate to the manufacturing process are already included in the optimal structural design process. It remains to define appropriate criteria for manufacturing and to include these in the mathematical formulation. In addition, as part of the integration effort, particular attention would be paid to the integration of optimal design software with geometric modeling software. The output of this research will, in time, provide enhancements to various applications software packages and aid in the development of new packages with much higher levels of integration.

The decision was made to emphasize optimization principles for several reasons:

(1) It is a leading basic research area in which university efforts in general and those of our faculty in particular are in the forefront. (The work of Anderson, Bernitsas, Kikuchi, and Taylor in structural optimization and Gilbert, McClamroch, Murty, and Papalambros in mathematical programming, optimal control, and design is particularly noteworthy.)

(2) It is an area with enormous potential for increasing productivity in industry when the results of this basic research are interpreted and organized in a form available to the designer.

(3) It lends itself well to integration with graphic and CAD concepts and procedures, thereby promising greater utility as a design tool. The research will use existing and developing industrial software packages, as appropriate.

(4) It can provide a ready platform for interaction with the research at the Design Laboratory and evolve a mutual testing environment.

A.4. SCHEDULE

Year 1

- Organize Design Laboratory and define specific research objectives and measures for evaluating the effectiveness of the research.

- Evaluate, select, acquire, and begin integration of initial hardware and software tools to be used in the Design Laboratory. Tentatively, an Apollo-based LAN with several commercially available applications software packages covering a spectrum of CAD/CAM activities is contemplated.

- Develop connection with manufacturing activities to select initial manufacturing requirements that can realistically be incorporated in the design process. Initiate first optimal design research incorporating these factors. Specifically use current UM research on design for assembly, casting, welding.

- Recruit students for the Design Laboratory course; counsel them into proper prerequisite courses for the Fall Term; enroll and teach them in the Winter Term; and obtain initial research results on the design process from study of the Winter Term group.

Year 2

- Evaluate research results from the first Design Laboratory experiment; revise research objectives and measures; offer second course in the Fall Term; repeat process and offer course in the Winter Term.

- Initiate parallel study with industrial design group; feed information gained in the Design Laboratory to this group and start feedback from it to the Design Laboratory.

- Continue development and refinement of hardware and software design tools; continue research in optimal design for manufacture and systems integration.

- Formulate first comprehensive definition of the design process problem and statement of needs for optimal systems integration.

Year 3

- Continue to evaluate, revise, and refine Design Laboratory in the Fall Term; repeat the process in the Winter Term; strengthen interaction with the industrial design group.

- Initiate first Ph.D. dissertations that take advantage of comprehensive definition of the design process problems and needs.

- Continue development and refinement of hardware and software design tools; step up pace of research in optimal design for manufacture and systems integration.

- Formulate revised comprehensive definition of the design process problem and statement of needs for optimal systems integration.

Years 4 and 5

- Launch comprehensive basic research in the areas and problems defined throughout the previous years.

- Formalize continuing interaction with industry for on-going research and education.

- Expand and integrate the Design Laboratory within the standard College curriculum. During the fifth year, a comprehensive evaluation of the entire effort will serve to define new goals, as necessary.

A.5. KEY INVESTIGATORS

Co-Principal Investigators:

P. Papalambros (MEAM)
J. Eisley (Aero)

Senior Investigators:

W. Anderson (Aero)
R. Keller (MEAM)
N. Kikuchi (MEAM)
D. Kochhar (IOE)
K. Murty (IOE)
T. Rao (MEAM)
A. Samuels (Art)
J. Stein (MEAM)
J. Taylor (MEAM)
N. Triantafyllidis (Aero)
G. Ulsoy (MEAM)

The biographical sketches of these key investigators are in Appendix O.

APPENDIX B. CELL-LEVEL PRODUCTION

B.1. OBJECTIVES

The objectives of this subproject are threefold:

(1) To integrate sensor technologies and intelligent control technologies with existing manufacturing technology to achieve a major improvement in the operational characteristics of an advanced manufacturing cell.

(2) To develop the technologies to integrate the operation of the cell with CAD and other manufacturing databases (for example, to use CAD-derived information to generate device programs).

(3) To construct experimental cells to demonstrate the viability of the techniques developed.

Two classes of demonstration cells will be developed. One will emphasize the integration of robots and machine tools into a generic cell that can produce parts with only stock and information from CAD/CAM and other design databases as input. The second will emphasize the use of multiple robots for assembly as part of a production cell.

The successful development of integrated production and assembly cells will have a tremendous impact on the ability of U.S. industry to compete internationally. First, the integration of multiple sensors, robots, and machine tools will increase both productivity and quality. Second, through the automatic generation of the programs to operate the cell, lead time for production of a new product can be reduced, reliability of the production process can be increased, and greater capability for linking cell operation with higher levels of factory automation can be achieved.

B.2. NATURE OF THE PROBLEM AND ISSUES

Current manufacturing is characterized by: (1) fixed and inflexible interaction among machines, tools, fixtures, parts, etc., with minimal capacity for automatic operation or adjustment and (2) a sharp distinction between design and operational objectives. This distinction is enforced by the division of individual responsibilities and by the lack of software aids to facilitate the integration of the two.

Future generations of advanced production systems will include integration of design and manufacturing and sensors distributed throughout the manufacturing environment. Such systems might consist of multiple machines, each performing a fixed type of operation (e.g., milling, cutting, drilling, grinding, joining); associated materials handling and storage devices for transporting parts, raw materials, and tools; multiple robots for parts handling and assembly; sensors and other instrumentation distributed throughout the production cell; distributed computing, communication, and control devices; and a link to CAD and other manufacturing databases.

There are a number of fundamental challenges in developing the technologies needed to realize the intelligent, model-driven, sensor-based systems of the future. While progress can be expected on some aspects in a few years, much of the research is long-term, with a wide range of problems to be solved. For example:

- *In-Process Sensing and Sensor Fusion:* This includes both the development of the sensors themselves and the analysis of data obtained from the sensors.
- *Process Control and Cell Optimization:* This includes both the use of process conditions to optimize production and control of multiple devices in the manufacturing cell.
- *System Integration:* This includes the design and implementation of a distributed, extensible, high-speed, real-time digital controller for managing multiple sensors and devices, and the integration of sensors and controls developed into demonstration manufacturing cells.
- *Cell-Level Programming:* This includes both automatic program and manual generation techniques, and linkage to CAD/CAM databases.

In-Process Sensing and Sensor Fusion

There are three aspects to in-process sensing and sensor integration: sensor development, sensor data processing, and sensor applications. Many of the sensors needed already exist but require better analysis techniques and computational capabilities. However, in some areas, development of new sensor technologies is required. Sensor data processing requires both signal processing to remove the desired signal from noise and data analysis to extract the needed information (such as visual or tactile image, surface texture, contact force, tool wear, etc.) from the measured data. Sensor integration, or sensor fusion, requires the estimation of variables based upon a synthesis of information obtained from essentially redundant multiple sensors and the estimation of variables based on indirect sensor information. The application of sensor information requires an understanding of the relationship between the sensed data and the process under consideration. Diagnostic sensing to determine where failures have occurred, process monitoring to anticipate problems before they occur, sensing for better understanding of process mechanics, and in-process inspection all require substantial research to be realized. Our initial efforts will concentrate on the analysis of sensed data and its application to manufacturing process control and robot applications.

International competition and the productivity crisis this country has faced during the past four or five years has led to a concentration of effort on sensor development for manufacturing and robot processes. New sensors for robots include force (Lee and Smith, 1984), tactile (Raibert, 1982; Harmon, 1982; Chun and Wise, 1984), range (Benton and Waters, 1984), and thermal, among others. Force and tactile sensing are critical for assembly operations. In a recent study, Harmon (1983) has shown that as much as 83% of small parts assembly tasks require tactile or force information for completion. Tactile sensors are relatively new. Such sensors have been based on optical techniques and variable resistance effects in polymers. Raibert (1982) and Wise (Chun and Wise, 1984) have built a tactile sensor based upon capacitive sensing that is approximately an order of magnitude more stable with respect to environmental conditions and has excellent pressure and spatial resolution.

Kegg (1984) has emphasized the importance of machine tool diagnostic sensing for autonomous operation of flexible manufacturing cells. A very promising area of sensing for process control is acoustic emission. Kannatey-Asibu (Kannatey-Asibu and Kornfeld, 1981) has investigated the relationships for acoustic emission data obtained from metal cutting and is currently investigating acoustic emission sensing for welding processes. Han and Ulsoy (1984) have studied the application of acoustic emission and force sensing for the determination of tool breakage in turning operations. In other situations, the sensing of motor current has been shown to be valuable for detecting tool breakage (Matsushima et al., 1982; Mohri et al., 1982). Pandit (1982) and Danai and Ulsoy (1984) have investigated strategies for sensing tool wear on-line, and Kannatey-Asibu (1982) has studied the use of acoustic emission sensing for tool wear and breakage.

Visual sensing is one of the most important sensors for robotics applications (Dodd and Rossol, 1979), and Brady (1983) gives an excellent overview. In activities relevant to the work proposed here, Mudge, Turney, and Volz (Mudge, et al., 1983; Turney, et al., 1984) have introduced a salient boundary segment matching technique that efficiently recognizes and locates an object even in the presence of partial occlusion. Future vision systems will be required to work in dynamic environments involving motion both of the objects in the scene being viewed and of the camera(s). For example, in assembly tasks, vision systems will have to track parts in addition to recognizing, locating, inspecting, and moving them. It has been demonstrated that in complex scenes some basic operations, such as edge detection and segmentation, can be performed more reliably by using techniques developed for dynamic scenes (Jain, 1983; 1984b). A new edge-linking and motion-prediction technique has also been developed that allows near real-time prediction and tracking of a robot using conventional image processing hardware (Eichel and Delp, 1984). Using the segmentation techniques discussed in (Jain, 1984a), one may obtain images of moving objects and compute required inspection or gauging information from the images.

Process Control and Cell Optimization

The essential goal of the research in process control is to seek techniques for the intelligent use of sensor-generated information for achieving improved operation of a variety of production processes. Control may be achieved from the value of a single parameter such as force, tool wear, production dimensions or it may involve multiple variables. There is a substantial capability for influencing the operational characteristics of the individual machines in a manufacturing process through use of sensor-based control (Hardt and Book, 1983; Koren, 1983; Ulsoy et al., 1983). Although such capability is technically possible, it is underutilized in current manufacturing technology. Improvements can be made through manipulation of variables such as cutting speed, feed rates, etc. Due to the inherent variability of the operating characteristics of most machines and the raw materials on which they operate, the use of adaptive feedback is essential if effective control is to be achieved (Ulsoy et al., 1983). If it is assumed that a part is routed among several machines contained in the cell, there is a more global problem of determining control variables in each machine, such as spindle speeds and feed rates, to achieve maximum productivity of the cell as a unit. There is also the question of how the cell should respond to a breakdown of a single machine, i.e., how the speeds and feed rates should be changed. These latter two problems are termed cell optimization. Since robots are expected to play an important role in advanced manufacturing facilities, research on robot control issues that are directly related to their role within the manufacturing environment is essential (Podolzky, 1984; Nagel, 1983; Brady, 1983). Typical applications of this class occur in robot control applications in which both contact force (or torque) and position constraints must be controlled, e.g., in insertion operations (Lee and Smith 1984) or screwing a nut on a bolt. Similarly, it may be necessary for two robots to move in synchronism, for example, in picking up a long rod. Simultaneous contact force and motion control along a path may be required, e.g., in the application of adhesives. In another application, one may need to control the torque with which a screw is turned while maintaining an appropriate orientation to the robot end effector. Problems of this nature and complexity are only beginning to be studied.

System Integration

Systems integration is one of the keys to the successful development of advanced manufacturing and assembly cells. Integration at two levels is required, at the component level and at the CAD/CAM/CAE database interface level. Both involve complex software and physical interconnections (Volz et al., 1984a; Wolter et al., 1984; Atkins and Volz, 1984). Work to address these problems involves both the building of tools to accomplish integration and the use of these tools for integrating demonstration systems.

At the hardware level, integration tools depend in large measure on the computational capabilities provided for the cell. Finally, it would be most useful if the distributed system could be programmed in one language with a single program spanning multiple processors in the system and the necessary data communications implicitly generated by the compiling process.

At the software level, integration tools revolve around the language(s) and operating system(s) used for programming the system and development of standard libraries of subprograms to deal with communication and devices in the system. The principal issues are the complexity of the software, its real-time performance, and the distributed nature of the system. Program and data abstractions (Hibbard et al., 1981; Hoare, 1972; Liskov and Zilles, 1975; Schuman, 1976) have been developed to deal with the complexity issues, and object-level design (Mudge et al., 1982; Organick, 1982) is becoming an important design methodology at both the software and hardware levels. These principals have been applied to a robot-based cell, with encouraging results (Volz et al., 1984a; Volz and Mudge, 1984). Among the conclusions of this work is the fact that program interactions among devices in the system are one of the biggest sources of complexity and difficulty in programming. Consequently, we now believe that it is very important to be able to program the distributed system in a unified way. In particular, the language system should allow the programmer to write a single program which spans multiple heterogeneous processors, with data communications implicitly generated by the compiling process. Several requirements are clear. Distributed sensors and control devices must be accommodated. The processing requirements of the sensing and control algorithms are sufficiently great that separate processors, in some cases special processors (Delp et al., 1982; Mudge, 1981; Mudge and Delp, 1982; Mudge and Turney, 1984; Turney and Mudge, 1981) must be assigned to them. The sensing and control applications may require fast real-time operation of the system, with cycle times on the order of 1 millisecond or less (National Science Foundation, 1982). Further, it is important that the system be able to accommodate new sensing and computing devices as they become available and be flexible in terms of configuration so that it can be adapted to many different cell configurations. In view of the time requirements and the volume of data that must be moved for some sensing applications, such as vision, a high-speed data-communications network is required.

Cell-Level Programming

The development of cell-level task-planning and programming techniques provides rich, but very difficult, areas of research. Ultimately, these issues should be resolved directly from the design and manufacturing databases. A simple example would be a generic data-driven machining cell in which both the NC program to run the machine tool and the data (e.g., how to recognize and pick up the parts involved) to drive a generic robot program are determined from the CAD database. Until this ultimate goal is reached, however, some form of manual programming will be necessary. The challenge here is to find powerful, yet user-friendly, programming techniques that can incorporate CAD-driven assists as they are developed. Graphics will be a critical tool here and one which will fit naturally with CAD.

Programming techniques for robots and machine tools are at somewhat different stages of development. Programming languages for machine tools such as APT or COMPAC II have existed for a number of years and have been widely used. Within recent years, there has been considerable effort devoted to developing techniques for deriving machining information directly from CAD databases, with some modest successes (Machover and Blauth, 1980). By comparison, robot programming is relatively primitive, and most robots are still programmed by hand-held teach boxes. Practical procedural off-line programming languages have only begun to appear (Summers et al., 1981; Vandenbrug, 1981; Shimano, 1979; Finkel et al., 1974). These off-line languages generally require a more skilled worker than the teach-box method. Moreover, they add significant debugging problems.

A natural extension of CAD to cell-level programming is the use of graphics. McAuto, Westinghouse, Calma, and a few other companies have workcell placement software that can simulate graphically each device in a workcell and show problems with interfering or nonreachable equipment. As part of this, it is possible to simulate the running of robot programs, with the robot movements displayed graphically. Relatively little has been done with generating cell and robot programs using graphics. McAuto and Automatix are experimenting internally with this type of work. The most extensive placement simulation work has been done at the Fraunhofer Institute in Stuttgart, Germany (Warnecke, 1984).

An experimental graphic programming system is in operation at the University of Michigan (Atkins and Volz, 1983). This system takes models of robots and objects to be manipulated from a CAD system and allows use of graphic input devices to adjust the viewing of the (simulated) workspace and manipulation of the simulated robot. The simulated robot motions generated by the user are both displayed graphically and translated into actual robot motion commands, which can later be used to drive the robot. Work is needed to include the programming of sensors, actuators, and non-geometrical constructs such as conditionals and looping. The link to CAD for purposes other than object/robot models needs to be explored. Our work on grip position determination and vision training (Volz et al., 1984a; 1984b) should be useful in this system.

Task planning is an extremely difficult problem to solve. The most comprehensive robot programming language ever proposed, AUTOPASS, was never implemented for this reason (Lieberman, 1975). Some progress, however, has been made on two subproblems:

(1) Effective path-planning algorithms have been developed for planar problems (Brady, 1983; Lozano-Perez and Wesley, 1979; Lozano-Perez, 1981). More recently, Hopcroft has examined particularly difficult special cases with some success (Hopcroft, 1982a; 1982b). However, these techniques do not extend readily to three dimensions. Brooks has developed some promising heuristic techniques that hold promise based on the use of generalized cones (Brooks, 1981). Another promising new technique based on optimal control and distance constraints is being developed by Gilbert and Johnson (1984), which, except for computational difficulties, is independent of the number of dimensions.

(2) The critical factors in determining a grip are non-interference of the gripper with the part or nearby obstacles and the stability of the grip (Brady, 1983; Paul, 1972; Asada, 1979; Wolter et al., 1982; Laugier, 1981). One of the most comprehensive strategies proposed is that by Wolter, Volz, and Woo (1984), which develops several criteria for good grips and an efficient scheme for performing the needed calculations.

The use of models to drive the operation of sensing algorithms is yet another important subproblem of building model-driven systems. Brooks, Greiner, and Binford (1979) have developed the Acronym System based upon generalized curves for representing objects and matching observed scenes against models. Bauman (1981; 1982) has explored both the use of models for driving SRI-type vision systems (Gleason, 1979) and more general use of CAD models in robot sensor systems. Volz, Mudge, and Woo (1984) have also implemented a system for training binary vision systems by CAD model information. A new class of vision algorithms is being developed by Turney, Mudge, and Volz (1984), which match CAD models of objects to those in an image in a least-squares optimal sense.

Some progress has also been made in the area of integrated model-driven cells. Volz, Mudge, Woo (1984) have developed a cell that combines the work mentioned above on automatic grip determination and vision training with a distributed object-based robot and sensor system (Volz et al., 1984a; 1983) to produce a generic model-driven part sorter. Within the limitations imposed by gripper size, the sorting of a new set of parts requires no reprogramming of either the robot or vision system whatsoever. Only user commands stating which parts are to be placed in which bins need be given; all other information is derived from the CAD database.

B.3. RESEARCH PLAN

The plan for achieving the research objectives depends on the development and synthesis of techniques from a number of disciplines; these disciplines include artificial intelligence, computer programming languages and techniques, optimization, machine vision, sensor technology, process control, and computer architecture. Substantial integration and coordination of the research will be maintained with research in other areas; this will be achieved by use of research participants with interests and expertise in several project areas, a continuing focus on the overall objectives, and the use of specific experimental testbeds to evaluate and motivate the research.

The planned research is a natural outgrowth and extension of work currently in progress at Michigan. Work is planned in each of the problem areas identified above, and an initial set of problems to be addressed in these areas is described below. Over a period of time, a broader set of problems will be addressed, with problem selection being guided by the long-term objectives outlined above, interaction with strategic planning and assessment activities of the Center, and interaction with the External Advisory Board.

The conceptual relationships among the subareas of research and the general philosophy with which the research will be conducted can be explained in terms of the conceptual testbed of Figure B.1. We plan to develop general, flexible, and extensible production cell testbeds of the form shown in Figure B.1. Two types of generic cells are planned, one emphasizing machining and one emphasizing assembly, though there will be many common aspects. Each will be a growing and evolving flexible system that can be used to test research developments in the principal areas identified above. A generic machining cell driven totally by CAD and other manufacturing databases is a likely development within a few years and will be a secondary goal of our research in conjunction with the research described in Appendix A.

The proposed advanced distributed digital controller is the operational center of the cell. The controller should be sufficiently flexible that it can integrate the activities of multiple sensors and devices and serve as a controller for clusters of robots, NC machines, and materials handling devices, as well as serve as the controller of the cell as a whole. Various sensors, as required for a given problem, will be attached to it. Each sensor will have its own control software unit to operate the sensor and to communicate with other software controllers. Similarly, interfaces to each device under the control of the system will be attached and will have software control processes within the digital controller.

There are two aspects to the linkage of the distributed controller to the CAD/CAM database. First, there will be a set of off-line programs performing various operations on

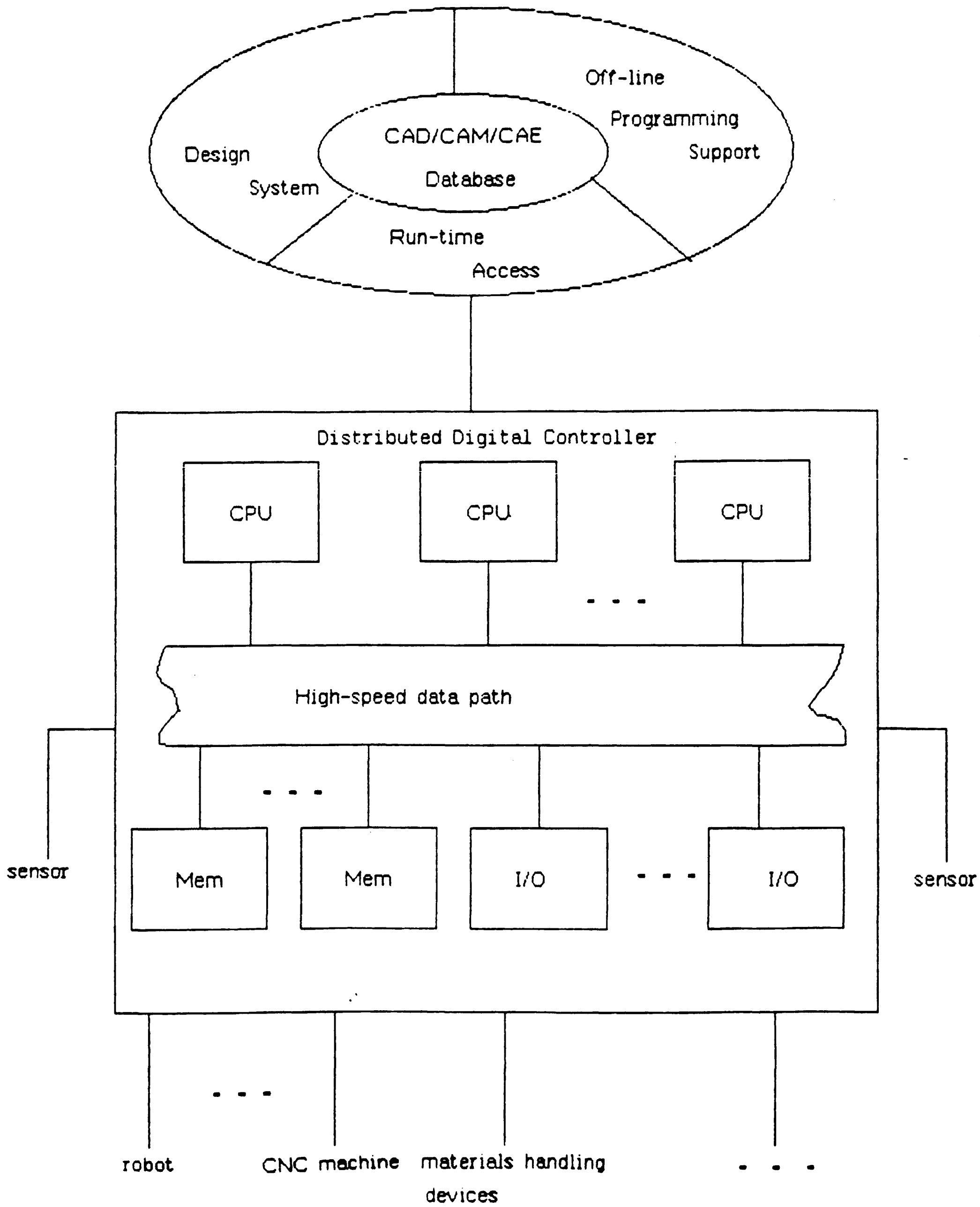

Figure B.1.

the design and manufacturing data contained in the database and producing information, such as gripping position for objects, training information for vision systems, program development, etc. These will be accessed and used by the controller. Secondly, there will be a set of access procedures by which the controller may access the database at run time. The research on sensors will yield devices to be interfaced to the controller.

The research on sensing will yield algorithms to be implemented as control processes associated with individual sensors. Process control research will also yield algorithms, to be implemented as software processes on the controller. In both of these cases, the software processes will be distributed and will require real-time interprocess communication.

In-Process Sensing and Sensor Fusion

Three current activities in sensing, which are extensions of current work, will be explored and implemented in our demonstration testbeds:

- Sensor integration for tool wear and breakage.
- Tactile sensing.
- Visual servoing.

Tool wear and breakage sensing have been attempted by a number of different techniques, but, as yet, no adequate solution has been found. Tool force, acoustic emission, motor current, and vibration sensing have all been used. In this work, we will investigate integrating all these techniques to obtain more reliable indications of tool wear and breakage. This, of course, requires a better understanding of how each of the individual sensor outputs are related to the state of the tool. An integral part of the problem is the development of techniques for processing multiple redundant sensor measurements to obtain useful and understandable information. For this purpose, the use of model-based statistical estimation procedures for filtering and suppression of noise will be considered. Estimation techniques for determining values of variables from indirect sensor measurements will also be a significant part of the problem. The implications of distributed processing and communications on the algorithms will also be considered. It is expected that the theoretical and individual experimental research will be largely completed in a two- to three-year time frame. Following that, the resulting tool wear and breakage sensing system will be integrated into one of the demonstration cells.

As noted above, a new type of tactile sensor is being implemented in our Microelectronics Laboratory (Chun and Wise, 1984). This work has focused on designing, building, and characterizing the device, not on applications of it. It has been found that the sensor, an array of pressure sensors, has extremely good environmental stability and pressure resolution. Future work needs to be directed toward analysis of the data obtained from the device and its application to various production processes. What techniques should be used for obtaining tactile images? Are visual recognition techniques adequate for tactile images? How accurately can an object's position be determined by feel? What texture properties can be felt by drawing the sensor over the surface of an object? Can slip be determined from the tactile sensor? These and other related questions will be investigated.

Visual servoing implies the need to visually follow in real time the motion of an object. While the usual techniques of edge-detection, segmentation, and recognition processes are too slow, recent edge-linking techniques and segmentation techniques based on consecutive images of a moving object (Eichel and Delp, 1984; Jain, 1984a) hold promise for real-time operation. In one recent experiment in motion prediction based upon vision, a vision system in our laboratory successfully predicted and followed the motion of a robot with update rates of two per second (Delp and Eichel, 1983). Extension of these techniques and their integration into a manufacturing cell should permit effective visual servoing to be accomplished.

Process Control

Control problems will be investigated for metal cutting and for robots in which contact forces directly affect the dynamics. Both are important problems in and of themselves, both have characteristics which are common to many other processes, and both will play an important role in the demonstration cells to be developed. The process control of metal cutting, in combination with the research on wear and breakage sensing, is important to the autonomous operation of a generic manufacturing cell. Correspondingly, simultaneous control of force and motion is necessary for robotic assembly operations.

Process control in the metal cutting area means simultaneous control of tool wear rate, cutting force level, product quality, and production rate. As noted earlier, the latter may be interpreted across several machines in a single cell. Of course, the achievement of these goals is closely linked with tool wear and other sensing techniques. Further, good models of how output variables are related to the sensed variables and inputs are required. Usually, the general problem is broken down into simpler subproblems (Koren, 1983; Ulsoy et al., 1983). The general process control problem has not yet been solved but is the subject of active research (Kannatey-Asibu, 1982; Ulsoy et al., 1983; Koren, 1983, Lauderbaugh and Ulsoy, 1984; Watanabe, 1983; Moon et al., 1983). The important problems to be addressed include process modeling and controller design for nonlinear, time-varying, multi-input, multi-output systems. The Mechanical Engineering and Applied Mechanics Department's Machine Tool Sensing and Control Laboratory has a CNC milling machine and lathe already instrumented for laboratory work that will be used in this study.

Relationships between forces and motion occur in many manufacturing operations, e.g., in assembly, joining, grinding, and machining. The simultaneous control both of a contact point on a surface and the magnitude of the contact force involves a number of difficult dynamics and control issues (Raibert and Craign, 1981). Adequate theory for dealing with these problems is only beginning to evolve and only for limited cases such as for frictionless contact (Huang and McClamroch, 1984). Key research issues include estimation of contact forces from indirect measurements, planning of reference forces, and force tracking based on indirect measurement.

Although our initial concern may be with improved sensor-based control of individual machines and individual robots, our ultimate interest is to control the multiple machines, robots, and materials handling devices in an optimized fashion, based on the distributed sensors throughout the cell. Such a cell-level controller involves machine coordination and management of failures or other emergency conditions. Such cell-level control issues are not currently being addressed, but they are of substantial importance. As advances are made in controlling individual devices, those advances can be incorporated into the cell-level control schemes.

System Integration

Development of a digital controller for the cell is the central feature of operation of the demonstration system. Its basic requirements are: high-speed real-time operation, distributed multi-processing, high-speed communication, flexibility, extensibility, modularity, and maintainability. Most of the above requirements are self-evident. A few, however, bear additional explanation. The processors in the system may not be assumed to be homogeneous. It is critical that the system be sufficiently extensible that it can accommodate special-purpose heterogeneous devices as well as replications of the principal processors used. Maintainability, particularly of the software system, is often overlooked. Yet in large embedded software systems, up to 70 or 75% of the total software cost goes into maintenance. The systems implementation language used for software development must support mechanisms to manage software complexity and make maintenance less difficult.

The approach we are taking is based upon the use of commercial products for the main processing elements. We intend to interconnect these in a multiple-bus, multiple-memory, multiple-processor configuration as shown in Figure B.2. This configuration permits multiple data paths between all elements, addition of processors to achieve the processing power required, and addition of memory as needed. A very general interface board will be developed to communicate in a standard way with the data bus configuration. Special processors will be mounted on the interface board on a one-of-a-kind basis as required. Individual processors in the system may also have links to external communication networks. In this way, multiple controllers may be interconnected as necessary.

The management of the complexity of the system is largely handled by the software system for the controller. Studies (Volz et al., 1984a; Bentley and Shaw, 1979; Browne,

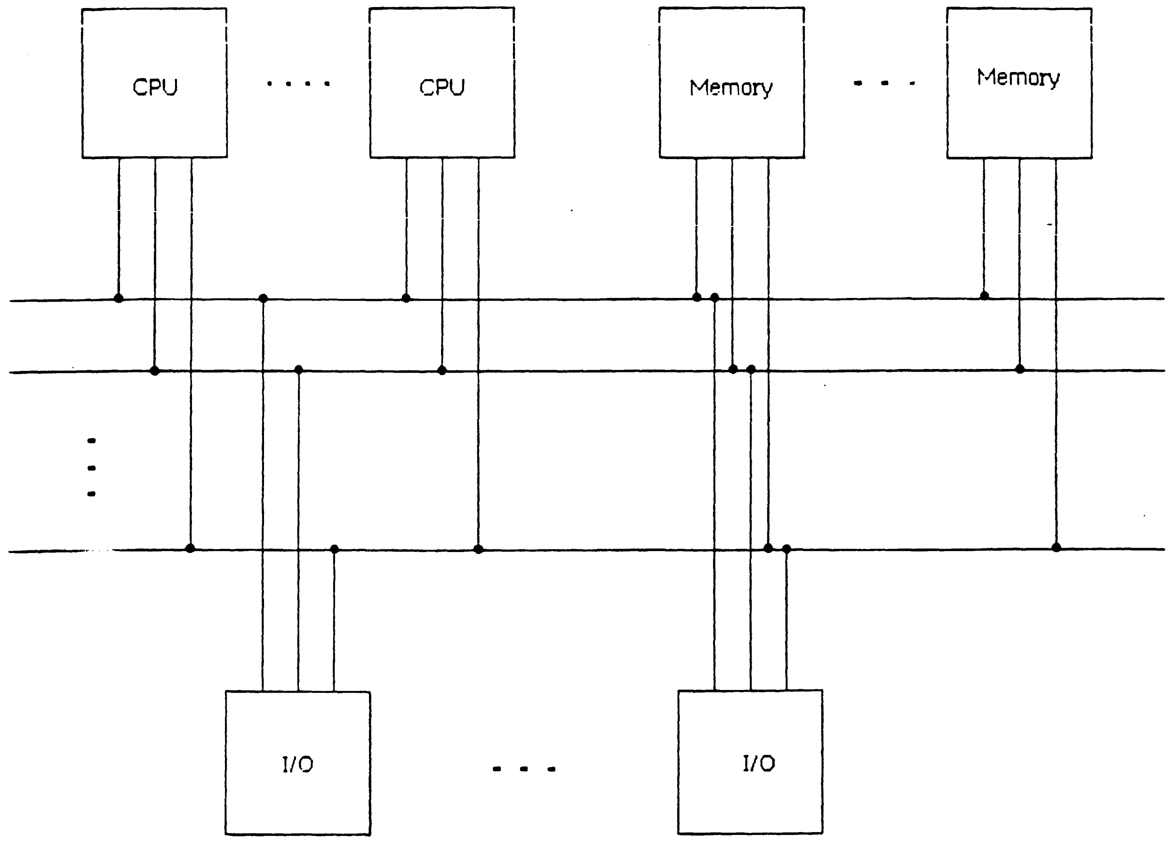

Figure B.2.

1980; Organick, 1982) have indicated that abstractions and object-oriented systems are required for the successful management of software complexity. The new language, Ada, was developed for exactly these requirements, as well as for real-time applications. Moreover, it has great potential for standardization. It therefore seems reasonable to closely examine the use of Ada as the basis for system implementation for the controller. On a current project, Ada is being examined as the basis for a distributed language, i.e., a language in which a single program can span multiple processors. We expect to make use of the results of that project in the distributed controller developed here. There are several important architectural issues regarding the real-time and communication aspects of the system. What should be placed in the run-time support package, and what should be placed in hardware? Where should special processors be used, say, for communications support, network timing, or distributed language support? These questions are currently being investigated.

Cell-Level Programming

The integrated model-driven manufacturing cell, as shown in Figure B.1, includes a run-time system (which includes all sensing and control functions) and a smart planning system (SPS) that provides off-line programming support. The SPS includes models of the run-time system components, an interface to CAD/CAM databases, and task planning algorithms. The principal problem being addressed is the development of the SPS. The problem is being addressed at two different, but interacting levels.

First as an extension of on-going research (Volz et al., 1984a; Wolter et al., 1984), the following tasks will be undertaken:

- Develop and implement techniques for maintaining a world model of all objects in the workspace of the cell.
- Develop and implement algorithms for obstacle-free gross-motion planning, based on models of the workspace contents.
- Develop and implement algorithms for fine-motion planning, including issues such as interference, slippage, and grippability.
- Develop and implement general heuristic problem-solving techniques and mechanisms for building expert systems.
- Develop an overall programming system capable of generating robot programs automatically.

There are, as shown in Figure B.3, two levels (gross and fine) of motion planning. The work in gross-motion planning will be directed toward defining the cell workspace with models of its objects and determining obstacle-free paths in that workspace. The fine-motion planning research will develop methods for identifying motion constraints and algorithms to translate these constraints into motion commands. Primary issues to be addressed are interference, slippage, twisting, and grippability.

The development of automatic programming and motion-planning algorithms will require application of artificial intelligence techniques. Automatic programming is expected to be based on an expert system, and general heuristic problem solving techniques will be required for subtask sequence determination. Irani (Irani and Shih, 1984;

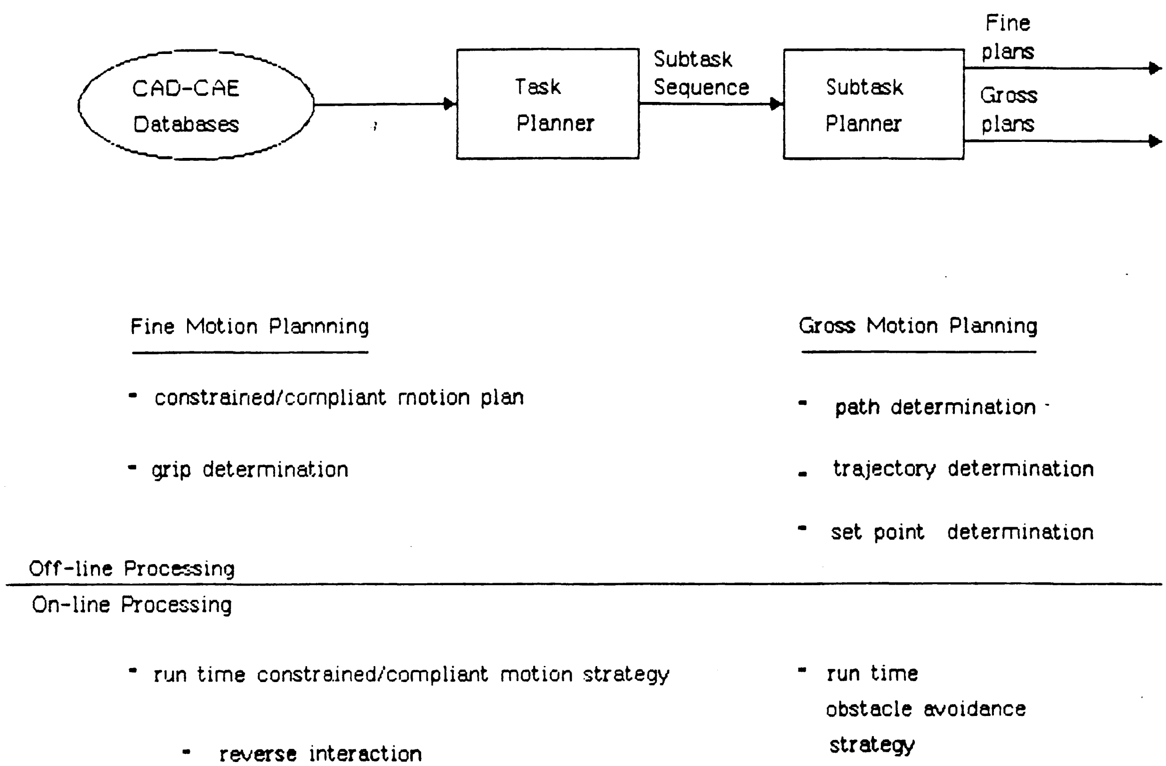

Figure B.3.

Shin and Irani, 1984) has made some recent progress in these directions.

Fully automatic graphical programming of manufacturing cells is a long-term goal. In the meantime, cell programming will continue to be an extremely important problem. Current programming practices are one of the chief causes of cell expense, inflexibility, and limited capability. It is also one of the places where significant progress is possible. Indeed, many of the intermediate results of the work toward task-level programming are applicable in a CAD-assisted manual programming system, e.g., automatic training of vision systems and grip determination. Consequently, at a second level, we are developing a graphical cell programming system.

The graphical programming system has the following basic components: graphics display system; object display and (graphical) manipulation system; translation system from graphical sequences into robot programs; and support utilities (e.g., editors, debuggers, etc.). Previous work (Atkins and Volz, 1983; 1984) has produced a basic graphic programming system that runs on low-cost microcomputer hardware, namely, an IBM personal computer. This system includes *some* of the basic elements of the first three components listed above. The system is far from complete, however, and additional work is needed in many areas to produce an acceptable working product. These include:

- graphical representation of sensor and actuator signals and operations
- graphical representation of program control structures
- graphical representation of cell components in addition to the robot and objects to be manipulated, e.g., machine tools, part transfer mechanisms, etc.
- debugging and simulation systems.

Each of these is a highly complex problem in its own right. Our research will begin with the first two of these and grow into the latter two during the first three years of the project.

The representation of sensors and actuators must include an icon that will provide easy recognition of the device, a method for locating the device on the graphics display screen, a method for representing the value(s) associated with the device, and, of course, a mechanism for including the sensor inputs in conditional and control actions of the program and similarly obtaining output values for actuators. Different techniques will be required for devices that have analog signals associated with them that can be used when only binary values need be considered. Control structures that need to be developed fall into several categories: conditionals, alternative selection, and repetitive operations. One can imagine various ways of combining icons with color to handle the case of binary sensors, but mechanisms to handle the other cases are less obvious. Indeed, the difficulties arise because operations to be presented graphically are inherently non-geometric.

While the first two operations focus primarily on detailed problems of programming the robot, the latter two are much more general in nature. Both require extending the simulation capabilities of the system. Debugging will require computational assists to determine potential collisions between the robots and other objects as the operation of the program is simulated. Further, the simulation must include the dynamics of the system; the dynamic behavior of many robots have been shown to be very different from the path planned by the simple path planners most robots use. The principal issue here is establishing an accurate correspondence between actual robot and cell motions for a program and the displayed motions of the simulation.

B.5. RESEARCH SCHEDULE AND INTEGRATION

Experimental research and the integration of our results into a larger context are two important aspects of our approach. The principal vehicles for this experimentation and integration will be two manufacturing cell testbeds, one for assembly and one for machining. In addition to providing the facilities and context for our experimental research, the testbeds will also be a focal point for interaction with other parts of this project, other related research contracts, and other organizations.

Figure B.4 depicts the anticipated relationship among the core research areas, the two testbeds, and some of the more important related activities over a five-year period. Growth of the project over this time is reflected both in the startup of new research problems in the second and subsequent years and in the growth of the testbed activities. The crossover lines show the points at which major transfer of results from the core research areas to the testbeds will occur, though there will be an ongoing interaction between the core research areas and the system integration (testbed building) activities. At least initially, with each of the major transfers, there will be a growth in the systems integration activity associated with the testbeds. In general, the personnel involved with the core research areas will also work with personnel in other technical areas in integrating their research into the testcells.

While the machining testcell will host numerous experiments, it will be developed over a period of time into a *generic* cell whose operation is totally driven by information in the CAD/CAM/CAE databases. Technically, this requires the full range of research described above. Moreover, it will involve collaboration with the product design and plant-level control aspects of the project, the former regarding the CAD/CAM/CAE database contents and format, and the latter regarding interfacing the cell to the rest of the factory. It will involve close collaboration with two existing research projects, one which is developing a distributed systems integration language and another which will provide some of the vision sensing, world modeling, and planning capabilities needed.

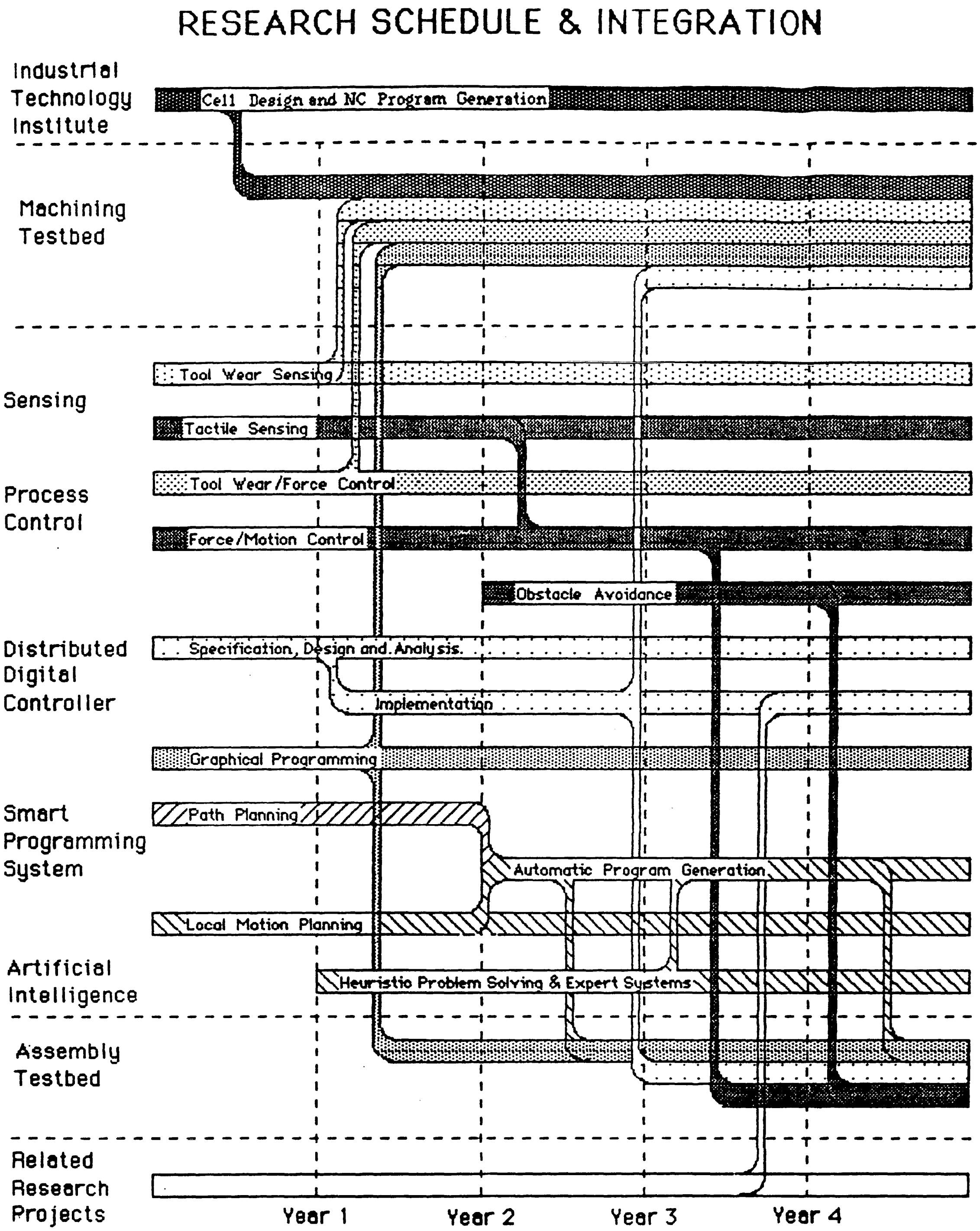

Figure B.4.

The Industrial Technology Institute will work closely with us on the development of this cell. They already have some of the equipment required, and will, by the time we are ready to use it, have the capability of generating NC programs directly from CAD data. This will be the machine program counterpart to the automatic robot program generation system to be developed in this project.

The assembly cell will also use most of the research activities in the core program. The long-term goal for this testbed is again to have a generic CAD/CAM/CAE-driven cell for assembly, in which the programs for performing an assembly operation are derived from the databases. Numerous intermediate results are expected which will allow significant CAD-derived assists in the program generation process, e.g., grip position or path determination. The interactions with the product design and plant control portions of the project will be similar to those with the machining cell, as will the interaction with the distributed language and vision/modeling/planning project.

The following paragraphs detail the year-by-year activities within the project.

Year 1

- Initiate research on effective algorithms for sensor fusion for sensing of tool wear and breakage. Also use tactile sensor previously developed for tactile image analysis.
- Investigate control strategies for the joint control of multiple output variables, considering tool wear and force for NC machines and force/motion for robots.
- Specifications for digital controller for cell-level control; conduct research on possible control/computer architectures; develop software specifications.
- Begin research on smart planning systems, emphasizing interference, path planning, and robot grippability issues.
- Extend previous research on use of graphics for cell-level programming to include binary sensor and repetitive operations.
- Design and develop the machining and assembly cells to be used as testbeds.

Years 2 and 3

- Continue research on sensing; emphasize the integration of sensor technologies with process technology results in context of the machining cell.
- Extend research on process control of NC machines to use advances in the sensor and sensor processing areas, and begin to incorporate the results into machining cell.

- Begin experimental phase of the joint force/motion research.
- Initiate research on cell-level control of multiple machines, robots, and materials handling devices, emphasizing coordinated control of multiple devices.
- Initiate the development of cell-level digital controller hardware and software.
- Incorporate path-planning and automatic grip determination results into smart planning systems software, including links to CAD databases.
- Extend graphic robot programming to handle analog sensors.
- Institute studies in application of artificial intelligence techniques to support task planning and program generation, e.g., heuristic problem-solving and expert systems.

Years 4 and 5

- The initial version of the generic machining cell should become operative during this period.
- Extend the research on process control of NC machines to cell optimization.
- Incorporate distributed language support into distributed digital controller.
- Place emphasis on automatic program generation for the smart planning system software.
- Integrate results of force/motion control and tactile sensing into assembly cell.
- Demonstrate model-driven automatic assembly of nontrivial product.

B.6. KEY INVESTIGATORS

Co-Principal Investigators:

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The biographical sketches of these key investigators are in Appendix O.

APPENDIX C. PLANT-LEVEL PRODUCTION: CONTROL AND DESIGN

C.1. INTRODUCTION

C.1.1. Control and Design

Taken broadly, "control" is a key to the factory of the future: adaptive control of machine tools, control of robots, control of material transport systems, real-time control and scheduling of the flow of material, parts, tools, and information on the factory floor, and even production-planning issues such as off-line scheduling, inventory control, material requirements planning, and capacity expansion. More important, this broad sense also includes the interconnection of these various kinds of control systems to form integrated manufacturing systems as well as the associated software. Finally, even in the most automated systems, it is often a human operator or decision-maker who will be the ultimate system controller. Thus the "factory of the future" will be made by welding together components — NC machines, robots, vision systems, material transport systems, and human beings — into a coordinated manufacturing system, with a control system at its heart. Control is the "glue" that holds the factory of the future together.

Design has two aspects. First, there is design of the product, in which the control issues considered here are pertinent. Products can be designed so that the control of their production is simplified — for example, chamfers on holes into which something must be inserted, process plans that are sensitive to the plant layout and its bottlenecks, and use of standard materials and fasteners. Design also applies to the control systems themselves: the topic of most of the activities described below. One approach to this kind of design arises when the plant layout and components are largely fixed, and the problem is to design a control system for this given situation. This process of retrofitting a control system onto given hardware can be extremely awkward, even impractical. Yet this design problem must not be ignored — there is a huge national capital investment in conventional manufacturing technology that is not going to be scrapped; the ability to retrofit controls with, perhaps, some minor modification of existing manufacturing facilities is required. The other approach to control system design is, of course, designing an entirely new facility along with its control system. Both this so-called greenfield approach and retrofitting and modification of an already existing facility are important topics for the ERC.

The general objective of this portion of the ERC is *to develop methods for plant-level control and design.* These methods will be demonstrated through design of testbeds, control of existing testbeds and industrial facilities, and simulation.

C.1.2. Three Levels of Control

We have chosen to characterize the design of control systems and, more generally, computer-integrated manufacturing systems by three levels: cell, factory floor, and production planning. A wide variety of similar hierarchical views of manufacturing systems and components appear in the literature (see, for example, Nof et al., 1979). We have chosen this rough but useful decomposition of the large and complex control problems of interest for two reasons: to be able to present our proposed research activities in a cohesive way and to emphasize that the interconnections between the three levels are of central importance. We use the phrase plant level to indicate the combination of the factory-floor and production-planning levels.

Cell level is characterized by a small number of machines in close proximity, tightly coupled, and with a great deal of interaction. Significant time intervals are short: microseconds up to minutes. Geometric coordinates, shape, and relative geometric position are important. Variables are often real valued. The cell level involves such physical details as adaptive control of a machine tool, the kinematics of a robot, trajectory planning, programming of NC machines, minimum-time control of a high-speed robot, tactile sensors, and vision algorithms. In a well-designed system, humans are "designed out," except for installation and maintenance.

The factory floor is a collection of cells, each with its own cell-level description. Here, concerns are with the flow of materials, tools, parts, and information throughout the manufacturing facility. Elements are somewhat more loosely coupled than in the cell level. Significant times are typically measured in seconds and minutes (e.g., the time required to load a machine with a part, to execute a part program, to move a part from one machine to another, to bring together two pieces for assembly). It is sufficient to identify a location by name, not coordinates; to characterize a cell by its capabilities; or simply "execute" programs for, say, NC machines and robots. Typical constraints are of the form "Only one pallet can be at machine #4." Variables are usually logical or integer. Humans may be needed occasionally to choose between alternative computer-originated control decisions or to intervene manually to keep the system going.

The interconnections between the cell and factory-floor levels are often in the form of commands to the cell level and status reports to the factory-floor level. For example, a material transport system can be commanded to move the pallet at A to B. A cell can report that a certain parts program has finished execution, or that it is so busy that estimated throughput times must be doubled. Of course, in some systems commands originate in the cell. For example, a cell may send the command "Send me more work." The design of this interface clearly affects design at the cell and factory-floor levels.

The third level is the production planning level, concerned with long-term scheduling, ordering of materials, manpower requirements, capacity planning, and so forth. Significant times are measured in days, weeks, and months. Location is usually not an issue; parameters of interest become more global, involving customer demand, economic factors, and availability. Even aspects of purchasing policy and vendor evaluation become of concern, and the human element becomes increasingly important, providing links with knowledge-based or expert systems.

The connections between factory-floor and production planning are also usually commands and status reporting, with commands likely to come from the production planning level and status reports from the factory-floor level. There are, naturally, variations on this theme.

Cell-level control, consisting as it does of a large number of related technical issues, is presented in Appendix B. Below, we elaborate on the ERC's proposed activities in plant-level control and design, that is, at the factory-floor level and production-planning level. Needless to say, there will be much overlap between these areas. Some of this integration is explicitly planned, for example, work on specific interface requirements. Other interaction will be a natural byproduct of the interdisciplinary nature of the research, particularly that involving experimental work on testbeds. Moreover, some people who work in this area will also be active in other areas, for example, at the cell level and in CAD.

C.2. FACTORY-FLOOR CONTROL

C.2.1. The Nature of Factory-Floor Control

We propose to develop and demonstrate methods of designing factory-floor controls. Current factory-floor integration is expensive and inflexible; as a result, existing "integrated" manufacturing systems do not realize their potential. One source of these problems, aside from those directly attributable to problems with the component cells, can be traced to software and to the lack of interface standards. Software is often expensive, inflexible, and deficient in intelligence. Without interface standards, the cost of developing interfaces one at a time is a deadening overhead that slows integration almost to a halt. Another source is the relative lack of understanding of appropriate algorithms for control and models for system evaluation.

Although both software and interface standards need considerable attention, the ERC will concentrate on software. Others are active in interface research, for example, General Motors with its MAP system (Kosmalski, 1984) and the National Bureau of Standards. The ERC will track standards developments and make contributions but will not take a leadership role in the interface area..

Our goal, software for the control of factory floors, implies supporting activities in system modeling, analysis, simulation, and algorithm development. We will demonstrate this software by a series of experiments on existing and proposed testbeds.

Our general approach to factory-floor control can be summarized by the following diagram:

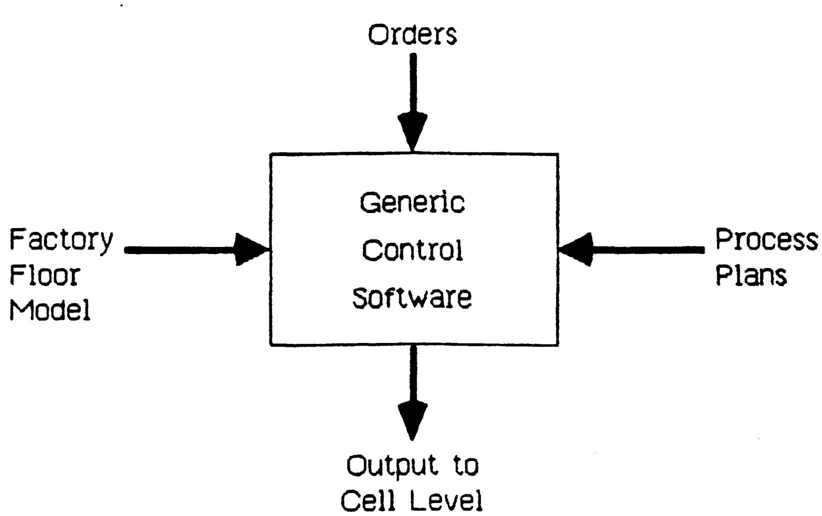

Figure C.1. Generic Control Software

In this case, orders (for example, "MAKE 25 OF PART NO. 7") enter at the top, a factory-floor model enters on the left, and process plans enter on the right. The output is directed to the cell level, where it is interpreted as "input" specifications or constraints (see Appendix B).

C.2.2. Research Plan

1. Modeling System

We will concentrate on developing an automatic programming system, specifically for modeling the factory floor and process plans. This must be able to model the flow of material, parts, tools, programs, and other information on the factory floor, as well as modeling system faults, times required for activities, and the probabilistic nature of the factory floor.

A prototype modeling system is currently being developed (Naylor and Maletz, 1984) for the design of the control software for the ITI Experimental Manufacturing System. Based on first-order logic, it treats parts, programs, NC machines, tools, messages, and steps in a process plan as entities that can be moved with respect to one another. In a sense, it models the factory floor as a game to be played by a control algorithm.

An important advantage of this modeling system is that it does not constrain subsequently developed control algorithms. For example, given a model for a factory floor, models for a number of process plans, a random stream of orders, and some measure of good performance, we have a precisely defined problem. This problem statement does not presuppose a solution method or technique. Developing the modeling system will involve a number of activities:

- Using the testbed models (see below) as part of an experimental framework for testing control algorithms. That is, we intend to develop modular control software in which the model is in one module and the control algorithm is in another. In that way, the control algorithm can be easily changed.
- Developing controls for testbeds
- Developing methods for representing models in memory and selecting appropriate languages for constructing models.
- Developing methods of automatic model generation. One way is to construct models at the time of factory-floor design. Another uses self-modeling, a system in which each component includes a model of itself that can be queried by a controller.
- Exploring the use of the modeling method in simulation. In particular, we propose to incorporate the actual control software in a simulation rather than a simulation model of the control software. This will allow use of simulation to investigate program correctness experimentally.
- Exploring the use of this modeling method at both the cell and production-planning levels.
- Continuing the theoretical development of the modeling method. This will include additional work on the logical foundations, use of temporal logic, automatic correctness checking of the model, and extension to expert systems.

2. Control Algorithms

One starting point for designing control algorithms is to assume a model for the factory floor, models for a number of process plans, and a random stream of orders. There are two levels of control algorithm that can result.

The first level, the simplest one, is an algorithm for controlling the specific situation described by the modeling system. The factory-floor model indicates the kind of information available from the factory floor and the kinds of moves that are possible. The only unknown from the start is the sequence of orders. With this sequence known, the control algorithm could be determined off-line. However, when a random sequence of orders is presented, real-time scheduling is required, and the basic job of the control algorithm is to decide what to do next.

If the model has provision for the factory floor "changing" (for example, machines failing or being taken down for maintenance), then the control algorithm becomes more complex, as it obviously should. The real-time scheduler is then faced not only with a random sequence of orders but a randomly varying factory floor.

The second level of control algorithm follows from a continuation of this line of discussion. We can envision an algorithm that will control an arbitrary situation: a randomly varying factory floor, an arbitrary collection of process plans, and a random stream of orders. Admittedly, this would be a difficult algorithm to develop, but we believe that it is a worthwhile course to pursue, and some part of our effort will be devoted to it. Such a control algorithm would have a major impact on the cost of software. Our approach will be to identify large, significant classes of systems for which the development of such an algorithm appears feasible.

Important aspects of control algorithm development are discussed next.

a. Stochastic scheduling sequencing and routing

To gain the full advantages of flexibility, the amount of each part to be produced and the desired sequence of those parts on each machine or process must be determined. Optimization of the sequencing of such events (Graves, 1981), applicable to both flexible machining and VLSI fabrication, can be viewed as a hierarchical system (Dempster et al., 1981). The top decision level is concerned with overall production goals, without regard to specific due dates. These problems typically are referred to as "aggregate production planning problems" for which existing techniques (see Hax, 1978) can be adopted. The second, operational decision level, is concerned with general schedules to meet the demand by the due date. (This is discussed below under "production planning.") The lowest level determines the real-time operation of the factory.

Real-time control of an integrated manufacturing process requires an efficient interface between the operational scheduling level and immediate part-routing level. Because the future operational condition of specific machines and the quality of the product produced (yield) are uncertain, this interaction can be modeled as a stochastic program or a Markov decision problem. Our research will use the known formalisms of these approaches to reach a specific understanding of real-time operational decisions. This will likely involve approximation and efficient heuristic development. Some progress has been made in this regard for large multi-user systems (Pollock and Birge, 1983).

In addition, in making routing decisions to minimize cost, process constraints and priorities must be considered. Cost can also be either local (e.g., cost of a specific high-priority wafer lot) or global (total throughput, with or without regard for profit margins). Yet cost may not be the sole parameter driving the decision process, so that there are multiple objectives in operating the testbed. Methods exist for linear versions of such stochastic multiple-criteria optimization problems (Birge, 1982), but little work has been done on related but non-linear scheduling problems (Pinedo, 1982). One difficulty is that no deterministic approximation may yield an optimal solution (Birge, 1982). A stochastic formulation considering all possible future outcomes will be constructed, and efficient methods for solutions developed.

b. Preventive maintenance scheduling

Most schedulers plan for operations during a time period in which demands are known. In integrated manufacturing, however, where machines must be finely tuned, maintenance and the availability of machines and even of entire cells are important parts of production. A production sequence should, therefore, take into account preventive maintenance schedules and unavailability due to failures. Some work has been done in determining optimal maintenance intervals (Chikte and Deshmukh, 1981), but little work has been done in incorporating these schedules into a production plan (Birge and Bayunis, 1982). In addition, almost all maintenance and repair will be performed by humans. A capability database must be developed, as well as an understanding of the relevant safety issues.

In determining these schedules, several factors are important, including the interdependencies among products and the reliability of machines. The ability to monitor performance and machine usage, either by using a simulation model or by actual operation of one of the testbeds, will be instrumental in achieving optimization in this area. Thus, the stochastic models (Stecke and Suri, 1984) of the components of the flexible machining cell (e.g., the input/output mechanisms, the machine tools, tool magazines, washers, gauges, controllers, etc.) and the VLSI fabrication line (the lithography, etching, washing stations, transport systems, etc.) will exhibit the mutual dependencies and interactions necessary to evaluate the system's probabilistic performance.

Such models will be the framework for developing maintenance policies consistent with higher-level system objectives of minimum cost or maximum throughput or constraints imposed by the operating requirements of the entire system. These will likely require extensions of existing Markov decision process approaches (Heyman and Sobel, 1984).

The investigation will also examine how estimates of reliability, maintainability, and availability can best be obtained when dealing with equipment that is either newly designed or being operated for the first time. Such techniques will involve effective and statistically supportable combinations of engineering judgment point-estimates, existing archival data on component behavior, and current operating data to provide a dynamic updating of model parameters (see, for example, Miller, Farell, and Pollock, 1984). The resulting availability and operability computations will have a major impact on the eventual design and operation of future systems.

c. Interactive routing

Given an overall plan and the current state of the system after an event (e.g., a process or transporter breakdown or unacceptable wafer yield or part inspection result), the next set of parts must be routed to avoid unnecessary delays. The goal at this stage may be to keep as many machines running as possible while the failed process is repaired and the system is reset. Or, it may be to satisfy some higher-level cost or productivity objective. The feasibility, for example, of maintaining buffer stocks of partially processed parts at particular points is one that will be studied, in particular by extending results from manual systems (see Maxwell et al., 1983, for a good bibliography). We will address this topic further in Section C.3. There are a number of other unanswered questions as to how to adapt existing re-routing methods to a truly integrated system. These include identifying appropriate definitions of operational objectives and constraints. For example, maximizing throughput is a legitimate objective only when the system will be operating essentially full time. Reduction of lead-time, however, may be an advantage only in terms of scheduling future procedures, such as assembly or shipping.

3. Software Development

Although ERC will not become involved in extensive software development projects, it will need to undertake a fairly significant software activity. In particular, software for the control algorithms discussed above will need to be developed and applied to the ITI Experimental Manufacturing System and the VLSI fabrication line.

So far we have discussed the control program as if it resided in one computer. This, however, will rarely be the case. In fact, there may be several thousand programmable devices on the factory floor. Thus, an important part of the design of the control system is the design of a distributed computing system. Research will not focus on distributed computing systems as such, but will be concerned with issues peculiar to factory-floor control, such as the balance between centralization and decentralization and how this affects reliability and information traffic.

4. Simulation of Plant-Level Systems

To study a wide range of alternative configurations of a manufacturing system in a shorter period of time than would be required with actual physical experimentation, off-line mathematical modeling activities are often appropriate. However, in view of the complexity of the systems to be studied, a reasonably high-fidelity model will itself be complex, probably precluding analytical treatment. Thus, simulation becomes an attractive technique. In addition to providing an ongoing tool for rapid analysis of physical scenarios, a general software simulation can serve as a stand-in testbed until the physical facility is completed.

Because existing simulation languages and methodologies may not meet these needs, more system-oriented tools must be developed. These may include, for example, representation of special material flow capabilities and graphics output of user-selected performance measures. Microcomputer capabilities should be present to allow for real-time specification of simulation conditions before implementing a particular set of commands on the factory floor.

Since automated systems may be designed to run continuously, the appropriate mode of operation of a simulation will be steady-state (Kelton and Law, 1984a, 1984b). Thus, care must be taken to choose data collection periods as well as starting conditions in the simulation to avoid biasing the results from the desired steady-state conditions. General techniques for accomplishing this (Kelton and Law, 1983, 1984b, and Kelton, 1984) must be adapted to the special conditions of integrated manufacturing simulation. These will be pursued in the ERC.

5. Material and Tool Transport

A critical component of manufacturing is material and tool transport. One example of a computer integration is a wire-based, minicomputer-controlled Automatic Guided Vehicle System (AGVS). The dispatching and routing commands must take into account the physical layout of cells and wires, as well as how the production schedule impacts on the demand for intercell material or tool transport via available vehicles. Given a fixed layout (machine and wire placement), production schedule, and number of vehicles, an algorithm for determining off-line a fixed set of intercell routes is being developed (Kelton, Smith, and Woo, 1984). This model considers transport time, congestion, and demand for vehicles, and iterates to maximize productivity, providing integration of the design and operational aspects.

In this model, routing rules are fixed; the route between a given pair of cells is always the same, regardless of the time or system status. The next step will be to modify this algorithm to choose routes in real time, accounting for the location of other vehicles, and possibly for the demand for vehicles in the near future (based on projected completion times of current cell operations).

C.3. PRODUCTION PLANNING

Production planning is a class of problems between factory-floor control and strategic planning. The time horizon may be measured in hours, days, weeks, or perhaps months as opposed to seconds or years. Within this time horizon, most factors of production are nearly fixed, and the objectives relate to planning production to best meet specified goals within the constraints of the existing system.

Major research issues include (1) scheduling production to satisfy output requirements while adhering to machine processing and material handling limitations on an aggregated basis; (2) determining appropriate buffers and levels of machine use to ensure that random disturbances such as machine or material handling breakdowns, yield problems, or late deliveries do not have catastrophic effects; and (3) procuring materials.

Solving these problems involves finding optimal short-term strategies for achieving production targets while planning in advance for randomly occurring events. One important reason for this planning is the adaptability it provides. Rather than having to replan comprehensively each time new orders arrive or a machine failure occurs, the strategies determined a priori can be used as a basis for making only necessary adjustments. As a side benefit, by planning in advance for randomly occurring events, fewer adjustments need to be made when these events do occur.

Therefore, factory-level control, problems discussed earlier, which are extremely difficult because of the amount of data and the multiplicity of objectives and constraints, can be made somewhat more tractable through the use of production planning. Thus, although technology exists to collect, transmit, and store large quantities of data, techniques do not exist for making optimal (or even "good") detailed scheduling and routing decisions in real time. We propose, therefore, to pursue two avenues of investigation: solving the short-term planning problems (to make the detailed floor-level problems easier to solve and implement) and collecting detailed data to provide a basis for "sanity checks" of aggregated short-term planning models.

C.3.1. Nature of the Problems and Issues

Models and techniques to optimize planned production schedules and buffers are not well developed for integrated manufacturing systems. There have been a number of recent developments on these problems in the context of Material Requirements Planning (MRP) Systems, which are used in large batch manufacturing environments (see Maxwell, 1983, for an extensive bibliography). Not all results and techniques, however, are applicable because the economic factors driving batch and integrated manufacturing differ, as do the primary sources of variability affecting the systems. For instance, large batch manufacturing is driven by high changeover times and/or costs, whereas in integrated manufacturing systems, changeover times may be relatively small; batch sizes are often determined by technological considerations. While both traditional and integrated manufacturing systems may experience variability of yields, supply delivery times, demand, and machine failures, the magnitude of their effects on the system are different. Integrated manufacturing systems are more susceptible to adverse effects of yield variability and machine breakdowns. In traditional settings, the production of infrequent large batches makes demand variability a major problem.

Much of the vast literature on scheduling for job shops and batch manufacturing systems (see Graves, 1981) deals with problems that can be stated as "Given a set of jobs to finish, a set of machines, and known, deterministic processing times, schedule (and where applicable, batch) the jobs to optimize the specified objective." The objectives generally are related to maximizing on-time performance or minimizing the average number of jobs in the system. Other approaches, which model some of the stochastic elements of the system, require simplifying assumptions (see for example, Pinedo and Ross, 1980, and Pinedo, 1981). Therefore, while some of the results from the literature may serve as starting points for investigating scheduling in integrated systems, other factors must be included in more realistic settings. For instance, some or all of the machines may be multi-function, and there may be more than one machine of each type, resulting potentially in a large number of possible routes. Material handling considerations must also be incorporated, including congestion delays and transport of multiple items simultaneously even when processing is done on a unit basis. Finally, rescheduling of tools and fixtures must be included.

There are two aspects of buffer determination. Type, size, and location are determined at the design level, based upon global considerations, as discussed later. The placement of buffer stocks in appropriate quantities at appropriate locations, so as to mitigate the effects of random events, are what we are concerned with here. Clearly, these two problems must be solved in a consistent manner. Buffer stocks will be limited by the size of the buffer, and the usefulness of the buffer stocks will be affected by their location (local or central storage). Consistency can be achieved by using two models separately (initially) to quantify the most important tradeoffs. It will then be possible to evaluate the effect of proposed buffer stock quantities upon the effectiveness and cost of the system as a whole, and the effect of limited buffer sizes on the ability of the system to operate effectively.

The determination of buffer stocks involves a tradeoff of the cost of holding the stock versus the "cost" of tardy completions or additional capacity required to ensure on-time completion. Related problems have been addressed for simple systems with a single type of uncertainty (See Lambrecht et al., 1982; Nahmias and Schmidt, 1983; Carlson and Yano, 1984; Yano and Carlson, 1984), but further research is needed to address more complex systems in which buffer stocks must mitigate the effects of multiple sources of uncertainty.

C.3.2. Research Plan

1. Scheduling

The scheduling component of this research will begin with an investigation of existing exact and approximate models (e.g., Graves, 1981), that may be adaptable to the integrated manufacturing environment. If existing approaches, tested in simulated testbeds, appear to be promising, the research will proceed with implementation on the physical testbeds. It is likely, however, that entirely different types of approaches must be used to handle realistic scheduling environments. By attempting to adapt existing approaches and using them on the simulated systems, we will be able to identify which aspects of real scheduling problems need to be addressed more effectively.

2. Buffer Stock Determination

Determination of buffer stocks will first involve studying the manner in which various types of uncertainty and variability interplay in complex manufacturing environments. It will also require developing better representations of "costs" of tardy completions than currently exist in the literature. Both analytical and computer simulation models will be used to address the problem. Although analytical models will be used primarily to optimize buffer quantities, and simulation models will be used to test the efficacy of these approaches, simultaneous development of both models is planned so that results from the simulation can aid in making the analytical model better represent the problem and to facilitate the development of useful optimization techniques.

C.4. PLANT-LEVEL DESIGN

The general problem of design of integrated manufacturing systems can be viewed in two contexts. The first is the design of completely new systems composed of multiple machines and material handling systems. The second context involves introduction of more advanced automation to a *portion* of an existing facility (retrofitting). The objectives of planning and design of facilities may be many, but generally can be stated as increasing the effectiveness and efficiency of the system *as a whole*.

The objective of the proposed research is to develop models of system performance as measured by cost, throughput, adaptability, and other relevant measures. These models will provide the basis for (1) understanding the various interactions in the system; (2) assessing the performance of a proposed system; and (3) ultimately optimizing the design of systems.

C.4.1. Design of New Systems

When new systems are designed, many decisions must be made including: (1) type, quantity, and rates of operations; (2) types of machines and tooling; (3) layout and operation of material handling equipment; and (4) location and quantity of local and centralized storage facilities. These broad descriptions encompass an enormous number of much more detailed decisions and specifications. Nevertheless, it is critical that these decisions be made with a systems perspective.

Many of these issues have been studied and modeled independently of the other factors. As examples, traditional objectives in plant layout problems are to minimize the total cost or time involved in transportation, or to minimize the sum of volume-weighted flows (Tompkins and White, 1982). These objectives generally result in layouts in which heavily used linkages are short and infrequently used linkages are long. This is quite reasonable in traditional systems, where, for example, workers walk the distances to transport materials. In other situations, however, this approach is inadequate if it ignores the more system-limiting effect of congestion on the link and the rates of production of the adjacent machines.

The selection of machine types is often severely constrained by technological requirements. In many instances, however, there are only a few alternatives. The problems of selecting machine types and, where applicable, the tooling for these machines, often are posed as "Given a set of items to produce, determine the best (most economical) machines (and tooling)." This approach to facility design does not consider what the machines may be used for in the future (i.e., the value of flexibility), nor does it explicitly consider the impact that the interaction among machines, and the interaction between the machines, the material handling equipment, and the human operators and service personnel may have on the ultimate efficacy of the system.

Similarly, decisions about capacities and number of machines are made with undue emphasis on "economies of scale" because of the traditional engineering economic analysis of single machines rather than entire systems. A group of smaller machines may have greater capital cost and require greater space and material handling equipment than one large machine but may provide significantly *reduced variability* of processing capability when machines are unreliable and/or tool breakage occurs. Because of the many interactions among components of an integrated manufacturing system, reducing variability is much more important than in systems in which components are largely decoupled.

Determination of local and centralized storage not only affects layout considerations but can have an enormous effect on the productivity of the system. As an example, insufficient local storage can result in "domino effects" upstream in the production process in the event of a machine breakdown, particularly if there is limited local storage and/or no mechanism to move work-in-process to central storage and back again. In addition, location of centralized storage area affects the degree of congestion on the material handling system and the time required to respond to unanticipated events such as machine breakdowns. Thus, indirectly, system productivity also is affected.

The analysis of appropriate ways to retrofit is similar to that for design of new systems, but the problems are somewhat less complex because fewer decisions must be made. Nonetheless, models of system performance can be used to (1) ascertain areas in which automation will provide the greatest net benefit and (2) quantify the effects on productivity and costs when a portion of the system is changed. This information must be obtained to use as input for economic analyses of equipment replacement decisions.

C.4.2. Research Plan

1. Framework for Evaluating a System Design

Because of the complexity of the design problems it will be necessary initially to carry on two parallel efforts. The first involves developing a framework for describing and evaluating system performance. This effort would incorporate as an essential feature the determination of <u>appropriate</u> measures of performance and identifying realistic and tractable modeling techniques. Measures of "flexibility" of integrated manufacturing systems (see Chatterjee, Cohen, Maxwell, and Miller, 1984) , as well as more traditional measures, should be incorporated into this modeling framework as it relates to design issues. In much of the existing literature (see Buzacott et al., 1980, 1982; Stecke, 1983), system performance is measured by "throughput," using queueing theoretic models, while other issues such as machine grouping and loading are addressed using nonlinear integer programming approaches. In most firms, however, meeting due dates is a more important goal than maximizing throughput. Queueing theoretic approaches cannot incorporate due dates explicitly. Nonlinear integer programming techniques can handle small sub-problems, but larger problems involving *systems* design are likely to be intractable both mathematically and computationally. Therefore, the development of a framework, while building upon past research, may necessarily take entirely different approaches. Rather than fit the model to a particular analytical technique, we plan to model the problem realistically and then develop new analytical techniques as necessary.

In parallel, we will investigate the interactions between system components that appear to be most critical in determining system performance. The emphasis will be on simple models of basic interactions, particularly those not studied previously.

2. Modeling Generic Integrated Systems

Having established a modeling framework and a better understanding of the various interactions, we can develop an approach for modeling system performance of generic integrated systems. The first stage will be descriptive, determining performance measures and quantifying various interactions within the system. The second stage will be normative, "optimizing" a system configuration, given a set of available equipment. At this stage, it will be necessary to incorporate appropriate long-term economic analyses very similar to those used for a single machine. Although the primary objective of this research is that of system design, there will be significant side benefits for the short-term production planning research activity. In particular, the descriptive model of system performance can be used as a short-term planning tool to aid in contingency planning for system disruptions and to quantify the effects of changes of operating policies or rules. In addition, as discussed earlier, the models developed in this research effort will be critical in providing cost and performance information required for longer-term economic analyses and cost-justification.

3. AGVS Design

One approach to system design will be to extend a current project that is developing a physical layout in concert with the intended operational characteristics of an automated guided vehicle system (Kelton, Smith, and Woo, 1984). A decision must first be made concerning route placement, as this is not easily changed. An existing algorithm assumes a prior fixed machine placement, and computes minimum distance routing links in a "taxicab" metric. However, to integrate the design and operational phases further, machine placement must be included as a choice variable. It is important to note that this activity feeds the routing algorithm discussed earlier (see "Interactive routing") to constitute an integrated methodology encompassing physical design together with operational design.

4. Modeling Human Interventions and Limitations

Although a major thrust of research necessary for planning future production operations will be to study and evaluate integrated hardware systems, comprehensive production planning methods must consider the variety of roles workers will be capable of performing in such systems. The Center for Ergonomics has developed and implemented models of workers performing a large variety of elementary industrial tasks. These human simulation models make it possible to predict how well workers of various anthropometric attributes can perform and are affected by industrial tasks requiring given reach, strength, motion time, endurance, and perceptual demands.

These worker simulation models will be enhanced and used to determine how humans can best be used and protected while servicing and providing manual back-up in future complex manufacturing systems.

5. Capacity Expansion Decision-Making

One of the most expense-laden aspects of system design is the decision as to when, and with what specific equipment, should a facility be built or upgraded. Existing methods, e.g., (Alchian, 1952), consider explicitly the improved productivity of future systems but do not account fully for forecasting errors and uncertainty about such productivity-affecting factors in manufacturing as the use of capital equipment, changeover times, required floor space, work-in-process inventory, etc.

We intend to extend this methodology to consider explicitly forecasting errors and data uncertainty. A secondary objective is to implement the methodology in one of the testbeds (flexible machining cell or VLSI fabrication) to judge its usefulness and effectiveness.

In 1982, Bean, Lohmann, and Smith (1984), extended the work of Oakford, Lohmann, and Salazar (1981) on finite horizons using dynamic programming to solve the infinite horizon replacement problem. This incorporates such factors as inflation, technological change, equipment degradation, multiple alternative systems, seasonal demand, and an unlimited number of cost (and savings) components.

Called DRE (Dynamic Replacement Economy), it has three principal advantages over previous models. First, it does not restrict the number of cost (savings) components (Alchian, 1952; Terborgh 1949). Second, it can solve an infinite service horizon without assuming that the current system(s) repeat identically (Canada and White, 1980; Grant et al., 1982; Newman, 1980) or partially (Oakford, 1970; Terborgh, 1949) into the future or assuming a long finite horizon (Oakford, Salazar, and Lohmann, 1981; Wagner, 1975). Third, it can be programmed to run on a microcomputer, permitting an analyst to perform a sensitivity analysis to evaluate some of the effects of uncertainty about the cost (or savings) components of the integrated manufacturing system.

The DRE method needs further development in two areas for it to be truly useful for integrated manufacturing introduction/replacement decisions. The first involves research into the effect of forecasting errors and data uncertainty. An important aspect affecting the usefulness of the DRE methodology (indeed all methodologies) is an analyst's inability to forecast future productivity. We propose to:

- Develop a procedure to identify the minimum forecast horizon (hence minimum data requirements) necessary to solve any particular replacement problem or class of problems.
- Assess the effect of errors in forecasting and data estimation on decisions about keeping the existing technology or installing a new system (Lohmann and Oakford, 1982).
- Develop a stochastic DRE methodology that formally recognizes uncertainty (rather than informally via sensitivity analysis).

The second area includes evaluating the usefulness of the DRE methodology by applying it to one of the Center's testbeds.

C.5. SCHEDULE

Year 1

- Develop prototype modeling system.
- Use preliminary modeling systems for testbed control.
- Develop off-line factory floor control algorithms.
- Formulate initial stochastic program for scheduling.
- Formulate FMS maintenance objectives.
- Identify optimal objectives for a selected testbed.
- Formulate buffer stock cost structure.
- Assess DRE methodology sensitivity to forecast errors.
- Start testbed simulation.

Years 2-3

- Develop framework for describing and evaluating general integrated manufacturing system performance.
- Test self-modeling to generate simulations.

- Complete simulations of selected testbeds (3).
- Test prototype algorithms on testbeds and simulations.
- Develop efficient computational methods for control algorithms.
- Complete data collection for reliability/reparability for selected system components, incorporate into maintenance model.
- Test buffer stock solutions.

Years 4-5

- Codify domain knowledge into "general rules" for assessing productivity and flexibility of manufacturing systems.
- Move toward semi-automatic generation of control algorithms for production equipment.
- Develop feedback channels for impacting effect on productivity on design.
- Develop management-oriented software systems for system design and economic placement/replacement decisions.

C.6. KEY INVESTIGATORS

Co-Principal Investigators:

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The biographical sketches of these key investigators are in Appendix O.

APPENDIX D. STRATEGIC MANAGEMENT

D.1. OBJECTIVES

The main objective is to link technical research on integrated manufacturing to industrial needs for improved productivity and quality and to the ERC program goal of enhancing U.S. industry's international competitiveness. The specific objectives are:

(1) To develop and apply comprehensive methodologies for evaluating the potential afforded by integrated manufacturing technology.

(2) To develop and demonstrate methodologies for determining where improvements in productivity and quality can best be made at present.

(3) To provide technology forecasts of integrated manufacturing and their strategic implications to industry and to CRIM.

(4) To develop a rationale and process for incorporating integrated manufacturing as a weapon in the strategic management of industries facing global competition.

(5) To suggest fresh approaches to the introduction of integrated manufacturing in the changing socioeconomic context of U.S. industry.

D.2. NATURE OF PROBLEMS AND ISSUES

To translate technological advances to competitive advantage requires strategic assessment, vision, planning, and action. Assessment requires measuring improvement in productivity, which, for this proposal, will be done in terms of economics — producing the "work" at minimum cost.

The lowest level of work occurs at the man-machine interface where a machine and a person assist each other. The contributions of the person and the machine are on a continuum from $O \rightarrow 1$, depending on the work situation.

The work organization consists of work elements intended to accomplish a specific task. The task is usually to produce a physical product or provide a service. The set of work elements that directly add value to the physical product or service are called <u>core</u> work.

A. Core work can always be identified as long as the organization or sub-organization has one or more specific purposes.

B. The major capital investment usually occurs in core work.

C. Core work contains the basic technology to be used in providing the service or product.

In addition to core work, organizations have support work, that set of work elements intended to help realize the full potential of the core work. Scheduling, maintenance, and personnel functions are examples. Thus, the measure of the need for and the quality of support work is whether it contributes to the realization of the potential of the core work. Other characteristics of support work are:

A. Each support activity uses a set of technologies.

B. The capital investment in support organizations is usually low compared with that in core work. Thus, technical change of support work is relatively inexpensive.

The quality of the "support" given by support organizations has not been well evaluated. Quality has two components: (1) the realization of the potential of the core and (2) the design and operation of the working environment within the support organization so that cost-efficient support is provided.

Core work using present technology is rarely as productive as it could be. For example:

1. The few studies that have been done reveal a lack of proper information in the core work, causing a reduction of approximately 20% in productivity (Hancock, 1982; Hancock, Macy, and Peterson, 1983; Karger and Hancock, 1982).
2. Lack of proper process controls in the auto industry have resulted in 20% to 30% losses in productivity, with substantial excesses in the size of inventories, scrap, and inspection forces (Hancock, 1983).

Organizations are investing in new technology for the core, when substantial short-term gains (20 to 40%) could be obtained by investing in the appropriate technology for support activities. As discussed below, a major segment of this study will focus on white collar productivity in product design, an area of understanding that lags far behind that for blue collar productivity. Because of the high systems and warranty costs incurred with poor design, the design function, especially the adequacy of the management systems, are coming under increased scrutiny (Liker and Hancock, 1984; Hancock and Liker, 1983). To be effective, the investment in new core technology requires concurrent understanding and modification of the support technology.

There has been little or no effort in the United States to develop methodologies for strategic assessments of purposeful work. Most of the productivity improvements have been fragmented attempts. Because of the hit or miss approach, many opportunities are being lost. We suspect that capital is being expended unwisely with unnecessarily high risks, and some new technology is being introduced without considering such side effects as occupational health and safety.

To move beyond assessment of current practices in design and manufacturing, one needs strategic vision, which can be enhanced by forecasting not only the technology of concern but also the strategic implications of the anticipated technological changes.

Technology forecasting is not an exact science. It is possible, however, on the basis of the dynamics of technological change, expert opinions, and certain assumptions about socioeconomic and technological trends, to make an informed judgment about the characteristics of future technology on the basis of the dynamics of technological changes, expert opinions, and certain assumptions about socioeconomic and technological trends. There are a number of methods for technological forecasting, each with its relative strengths and weaknesses (Martino, 1972). The experts in CRIM are particularly experienced in projection from R & D results based on informed engineering judgments (Wise, Chen, and Yokely, 1980) and in using the concept of technological generation dynamics (Chen and Chang, 1984). The Industrial Development Division (IDD) in UM has used the Delphi technique (Linstone and Turoff, 1975) to conduct a continuing series of surveys related to manufacturing technology issues — CAD/CAM, robotics, assembly systems, and future trends in the auto industry. It would be a challenge to combine the strengths in these various methods to forecast not only the future technology for integrated manufacturing but also its strategic implications. The results of these forecasts could then be used by industry to consider competitive strategies and by the researchers and the Management Committee in CRIM to assess and guide the Center's research program.

Strategic vision is an explicit blueprint for success, specifying what a particular organization is and should be (U.S. Congressional Foresight Task Force, 1983). Thus the results of the technological forecast will be useful to any U.S. manufacturing firm as it develops its own strategic vision based on its specific competitive position. The strategic vision should be translated into a strategic plan in order to motivate consistent decisions by managers. The rationale and process for strategic *planning* in the context of new technologies are generic issues that cross-disciplinary research can facilitate its use in all U.S. companies. It has been pointed out (Roberts, 1983) that corporate strategic planning has evolved from a focus on financial issues (in the 1960s) to marketing (in the 1970s) and now to technology (in the 1980s). A number of fundamental research issues in technology-based strategic planning have been identified but not yet resolved. For example, how can technological planning be most effectively integrated with other aspects of corporate planning? The Integrative Corporate Planning Program (Chen and Prahalad, 1983) recently launched by UM's UTEP Program (see Appendix K.6 for details) has begun to take on this research question with industrial sponsorship and participation. A research issue central to integrated manufacturing is how the current rationale and process for strategic planning should be modified to take into account anticipated changes in design and manufacturing process technologies. For example, how do we decide how a car or semiconductor company can improve its competitive position from the exploitation of these process technologies?

A strategic plan is only a piece of paper until it is effectively implemented. A company can develop and acquire a powerful integrated manufacturing technology only to see it wasted. It is often said that the U.S. has superior technology but that human and institutional problems stand in the way of its full utilization. We are, therefore, concerned with strategic decision making that affects implementation and diffusion of integrated manufacturing technology. This focus includes both intra-organizational decision making as well as interorganizational relationships. Our prior work in this area suggests the importance of conducting social and technological planning together to maximize organizational performance (Cole, 1984).

Sociotechnical innovation is particularly critical to the success of technology in the degree of integration between design and manufacturing. Failure to ensure the systematic and continuous exchange of information between these two functions has resulted in a number of problems: the production of difficult-to-manufacture products (large number of engineering changes, "fix it on the run"), design cycles, delivery delays, and quality problems (Voegtlen, 1974). At the root of these problems are failures of communication, negotiation, and decision making between the affected units. The basic research questions concern the extent to which integrated manufacturing technology will automatically address these problems, or whether the success of this technology will be heavily dependent upon the implementation of new organizational arrangements.

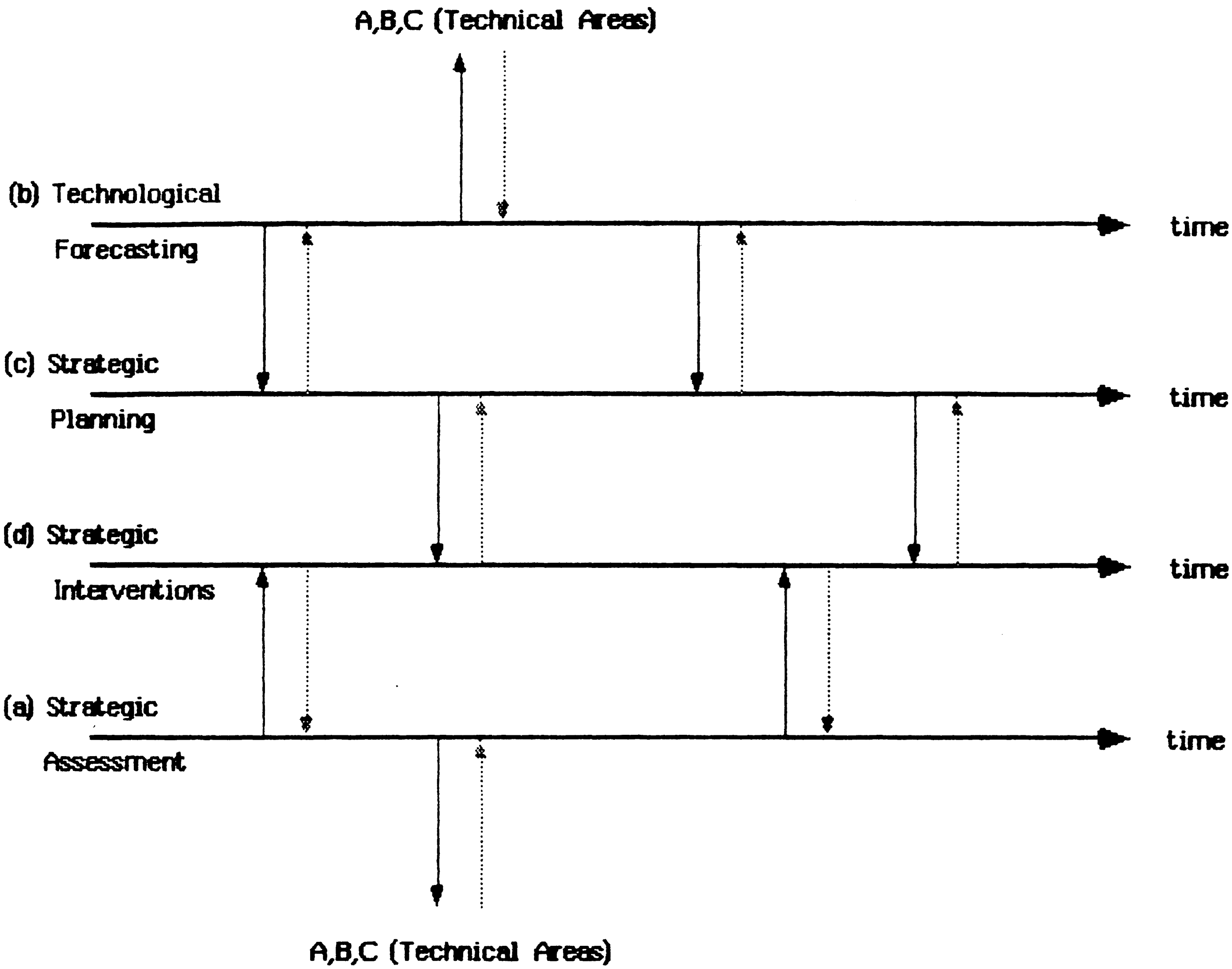
In our research on both strategic planning and strategic management of change, we intend to explore the extent of industry differences. In accord with the overall design of our research strategy, we will focus especially on the automotive and the semiconductor industries because of the contrasts between their technocultures, as illustrated by the following table:

	Automotive	Semiconductor
Technology introduction	Evolutionary	Revolutionary
Labor force	Older	Younger
Financing	Established institutions	Risk capital
Engineering	Design dominant	Manufacturing dominant
Management	Vertical	Horizontal

In addition, we intend to examine the differences between larger and smaller firms, often suppliers to the auto industry.

D.3. RESEARCH PLAN

Four investigations will be conducted simultaneously on strategic assessment, technical forecasting, strategic planning, and strategic intervention, all related to integrated manufacturing technology. The interrelationship among the four parts within this research area and their interactions with the other three areas are shown in the following diagram. The solid arrows indicate the primary flow of information: technological forecasting results going into strategic planning, which precedes strategic intervention. Strategic assessment will also suggest specific intervention and, along with forecasting results, will be used for strategic guidance of the technical research projects in the other three research areas (A, B, and C). The dotted arrows indicate feedback or secondary flow of information. For example, the feasibility of fresh approaches to strategic interventions may lead to an entirely different framework for strategic planning. The design of forecast questionnaires will require inputs from experts working in the technical areas, etc.


A,B,C (Technical Areas)
(b) Technological Forecasting
time
(c) Strategic Planning
time
(d) Strategic Interventions
time
(a) Strategic Assessment
time
A,B,C (Technical Areas)

Diagram

D.3.1. Strategic Assessment

Two methodologies will be developed. The first is a comprehensive methodology to strategically assess what areas need to be improved to realize the full potential of the core technologies. The second is the further development and demonstration of a survey methodology based on a work design to aid in the assessment of white collar work forces, with special emphasis on the design engineering function.

A. The Strategic Assessment of a Work Organization

Our research design includes three steps:

1. Select work organizations that are producing physical products and determine through the use of the methodology:

   a. The potential productivity of the present core work, assuming there are no impediments.

   b. The present productivity. Since output is a physical product that can be measured, hard measures such as machine utilization relative to capability, defect rate, etc., can be used to detect problems that can then be traced to assignable causes. It is in the area of assignable causes that the greatest potential contribution may lie, since there is no known method for systematically assigning causes to production inefficiency. Among the assignable causes may be problems in the support organization (e.g., maintenance, design engineering, labor relations, etc.). In this case, an investigation will be made of the support organization responsible for the problem.

   c. The technologies and the costs necessary to remove the productivity inefficiencies in b. above. Special emphasis will be given here to integrated manufacturing technology. If the subject organization has integrated manufacturing, then special efforts will be made to determine if its use has improved the output of the core. If the organization does not have integrated manufacturing, a special effort will be made to determine if its implementation would likely increase productivity.

   d. The support organizations that appear to be oversized in comparison to their contribution in realizing the potential of the core work.

e. The sufficiency of the workflow processes within the core activities.

f. The impact on productivity of changing the organization and technologies proposed in d and e above.

g. Improvements in the core technology that would provide the most improvement in productivity.

h. Participation with the organizations studied in the improvement of productivity.

i. Revaluate productivity to see if the productivity improvement efforts had their intended effects.

j. Publish the results with an attempt to generalize the separate studies into a comprehensive methodology.

2. The study design would be two replications of two core processes (i.e., four studies) to determine productivity improvement similarities between core processes.

3. Typical core processes would be automotive assembly, stamping operations, or such machining operations as a crankshaft line. Since the auto industry is becoming increasingly involved in microelectronics, there may be opportunities to study microelectronics processes. Geographical location will be a key here, because frequent site visits will be necessary. Using the knowledge base from steps 1 and 2, we would work with two organizations that are attempting to develop new production facilities involving the core processes or improved processes studied so that the productivity methodologies can be used where the impact will be the greatest — in a newly designed facility.

B. The Strategic Assessment of the Design Function

The design function will be singled out for separate study because of its critical importance to technological innovation and the quality of products. Since the output of engineering cannot be counted and assessed as physical products, new methodologies must be developed for this assessment. In recent papers (Hancock, 1982; Hancock, Macy, and Peterson, 1983; Liker and Hancock, 1984; Hancock and Liker, 1983), the co-investigators have described the development of a survey-guided approach to assessing whether the work environment of professional/technical workers is conducive to productivity.

The unique aspect of this survey is that people doing the work are presented with design criteria for how their organization should be functioning (e.g., before beginning an assignment you should have all the information needed to do the work) and asked to compare their situation to the ideal. In this way, respondents are presented with a standard for comparison, and we can thus detect productivity deficits (e.g., the difference between the productive potential and actual utilization of the support organization.)

The methodology above, in principle, can be applied to any work unit. Because of the critical importance of design engineering in contemporary technology-driven organizations, we will focus initially on the design functions. It is becoming generally recognized in many industries, and specifically in the automotive industry, that poor engineering design is the source of critical downstream production problems and warranty claims. These industries are going through rapid changes in organization and technology, and careful consideration of the implications of these changes for the design function will be crucial to the industry's success.

C. Integration of Core and Support Assessments

An attempt will be made to conduct the studies of (A) and (B) above in the same company. This will have a number of advantages. First, each assessment provides a validity check for the other. For example, if the engineers surveyed perceive that the engineering organization is deficient, causing inefficiencies in the core processes, but the assessment of core processes does not confirm this, much can be learned by investigating this discrepancy. Second, even if the core organization is highly productive, the engineering design group may not be developing new products to their capability. Third, the two assessments provide an opportunity to investigate the interaction of design and manufacturing.

D.3.2. Technological Forecasting

A combination of forecasting methods will be developed with the aim of fully utilizing both the researchers associated with CRIM and the different kinds of relevant experts in industry. A preliminary forecast will be obtained initially by reviewing pertinent literature, interviewing knowledgeable researchers (including but not restricted to those within CRIM), checking against basic engineering and scientific principles, and applying the concept of generation dynamics. The technological forecast will be focused on the critical elements of integrated manufacturing technologies in CRIM's technical research programs, but the study of strategic implications will be wide-ranging. The choice of CRIM's technical programs has gone through several years of discussion with experts in the world, but the strategic implications are relatively unexplored. In order to benefit from a wide range of perspectives, the preliminary forecasts will be used for designing a set of Delphi surveys, which are characterized by anonymous interaction, iteration with controlled statistical and commentary feedback, and statistical group response. Care will be taken in selecting knowledgeable panelists for the surveys.

Two separate forecasts pertaining to integrated manufacturing technology and strategic implications are to be conducted as an information base for subsequent strategic planning efforts. These forecasts will establish trends in integrated manufacturing technology, and their strategic implications. The first Delphi survey will use a panel of experts who are vendors, users, researchers, and "information gatekeepers" (e.g., technical journal editors) of relevant technology. For the second survey, four separate panels are to be established, each to consider a different aspect of CAD/CAM. The first, composed of salaried engineers familiar with CAD technology, will consider design process (CAD) technology; the second, with shop-floor engineers and technicians, will cover manufacturing process (CAM) technology; the third, with industrial schedulers, production planners, and controllers will examine planning and operations issues, including equipment integration and optimal utilization; and, finally, upper-level management, combined with labor relations experts, will consider the strategic management issues associated with integrated manufacturing, including deployment and development of human resources. For this second survey, a computer conferencing network, using the established CONFER (a UM software), will be used to conduct the survey. This has a two-fold advantage: it vastly reduces the time required to conduct a round of questioning, and it allows direct, though still anonymous, dialogue among panel members.

D.3.3. Strategic Planning

We will first establish channels for continuing communications with strategic planners and decision makers in the automotive and semiconductor industries. The initial communications will permit the exchange of concepts and experiences in technology-based strategic planning between UM researchers and industrial participants. Case studies conducted in a number of mature and growth industries will be jointly reviewed to identify new planning methodologies and innovative planning processes that have worked particularly well or poorly and to understand the reasons for success and failure. Any difference in current practices between the auto and semiconductor industries will be analyzed in the context of their technocultures, as well as the characteristics of their competitive environments. Next, the strategic planning process in selected companies will be observed as the process is triggered either by time or by events (Ansoff, 1965) related to integrated manufacturing technology. We will find out how these companies intuitively or systematically relate design and manufacturing technologies to productivity and quality improvements, how they assess the strategic utility of these technologies in terms of the instrumental goals of shorter lead time, fewer mistakes in design and manufacturing, etc., and how they make economic and other less tangible tradeoffs among these instrumental goals in comparing technological alternatives. We will observe the process of information flow, the development of corporate strategies, and the strategic decision making that are related to integrated manufacturing. We plan to compare the characteristics of such processes across industries (especially auto and semiconductors) and across countries based on what we will have learned from the literature, (e.g., Cole and Yakushiji, 1984; Chen, Eisley, Liker, Rothman, and Thomas, 1984), and other sources.

We plan also to use the preliminary results from the other two parts of this project as possible triggering events. Thus, the results of the first set of technological forecasts will be used to simulate a triggering event to test how the current strategic planning rationale and process would take new integrated manufacturing technology into account. Deficiencies that become apparent in this test will lead to suggestions for new approaches. Cross-fertilization between suggested improvements for the auto industry and those for the semiconductor industry (and between U.S. and other countries) is expected.

The UM researchers plan to participate in the implementation of the suggested improvements, with a view toward evaluating them and making suggestions for further improvements. Before this repetitive evaluation-suggestion process (using forecasting results as the triggering events) proceeds further, attention will be given to sociotechnical innovation in integrated manufacturing (the fourth part of the project) as another type of triggering event. In this case, the strategic planning rationale and process will be tested for their capability for anticipating and adjusting to difficulties at the implementation stage.

D.3.4. Strategic Interventions

In considering the changes critical to the successful adoption of integrated manufacturing technology, we will focus on the process of change in large organizations — (Prahalad & Doz, 1982). In particular, we will pursue the implications of these system information needs for the individuals in contact with the system, as well as the appropriate distribution of access to the system, whether for providing or using information. Our second task will be to identify those changes actually associated with the adoption of integrated manufacturing technology. This will include a consideration of cross-functional interchanges, multi-skill capabilities, participative work practices, changing career lines, reward systems, and training requirements. The work of Majchrzak and Nieva (1984) will be helpful in providing a model of effective sociotechnical innovation appropriate to integrated manufacturing technology. In particular, we are interested in gathering data that show the possibility for modification of the technology to meet the needs of the social environment as well as enhancing the company's economic benefits. The result of this fourth task will be fed to the researchers working on the technical projects in CRIM and will also be published for wide circulation.

In all these research activities we intend to explore the extent of industry differences, especially between auto and semiconductor industries, and between larger and smaller firms. We will examine similarities and differences in sociotechnical innovation and isolate the impact of the differing semiconductor and automotive technologies on the options available for the use of integrated manufacturing. The null hypothesis is that there are no differences between the semiconductor and auto industries (intra-industry differences will be greater than inter-industry differences). We will devise and apply objective measures of integration to each firm. In addition, we will explore the process by which integrated manufacturing does or does not become adopted by smaller manufacturing firms, especially those serving as suppliers to the large research-rich companies. The goal will be to identify obstacles to such diffusion among smaller firms and innovative strategies for overcoming them.

D.4. SCHEDULE

A. Year 1

- Perform the strategic assessment of a work organization and the design function.
- Determine impediments to productivity and design of the work organization.
- Complete a preliminary integrated manufacturing technological forecast.
- Complete an exchange of concepts and experiences in technology-based strategic planning with selected companies.

- Complete an investigation of information needs and flows in selected areas where adoption of integrated manufacturing technology is being considered.
- Integrate knowledge gained into the relevant courses.

B. Years 2 and 3

- Perform A.1 and A.2 above in two other situations.
- Select a new design situation for a manufacturing facility and use the methodologies developed in the strategic assessment subarea to influence the design.

  Complete Delphi surveys of integrated manufacturing technological forecasts and their strategic implications.
- Complete an analysis of strategic planning rationale and process with respect to technological change in integrated manufacturing.
- Complete construction of a model of effective sociotechnical innovation appropriate to integrated manufacturing technology.
- Summarize the productivity of the design function studies.
- Initiate graduate seminar, Strategic Assessment of Productivity.

C. Years 4 and 5:

- Perform A.1 and A.2 above in one additional situation.
- Participate in at least one other new design situation for a manufacturing facility.
- Summarize the design function productivity studies with special attention to CAD/CAM. Provide comprehensive methodologies.
- Attempt to generalize strategic assessment studies replications to develop a comprehensive methodology.
- Complete an integrated manufacturing technological forecasting system, using computer conferencing to speed up the forecasting process, demonstrating continuously updated forecasts of technological change and its impact.
- Complete one or two trials of improved rationale and/or process of technology-based strategic planning.
- Complete comparative analysis of most appropriate sociotechnical innovations for integrated manufacturing between industries and between large and small firms in the same industry.

D.5. KEY INVESTIGATORS

Co-Principal Investigators:

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W. Hancock (IOE)

Senior Investigators:

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R. Cole (Sociology)
J. Liker (IOE)
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D. Smith (IDD)
B. Talbot (BusAd)

The biographical sketches of these key investigators are in Appendix O.