Abstract: This is Volume 1 of a two-volume report on the global competitive environment U.S. manufacturers will face, and the infrastructure it will require, in order to compete as it moves over the next 15 years into the 21st century. The distinctive value of this particular document lies in its presentation of a comprehensive picture of a new system of manufacturing - agile manufacturing - that has begun to emerge in the industrially advanced nations. The opportunity and the vision chapters together provide the backdrop for four inductrial scenarios. Each is written from the perspective of a successful manufacturing enterprise in the year 2006. Together, the scenarios identify the technological, managerial, and social infrastructures that will have to be put in place if such enterprises are to come into being. Volume 2 of the report amplifies the technical details implicit in the creation of these infrastructures. The key finding of this report is that there is a common infrastructure requirement for all agile manufacturing enterprises, regardless of their industrial sector.

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www.parshift.com/s/21stCenturyManufacturingEnterpriseStrategy-Volume1.pdf
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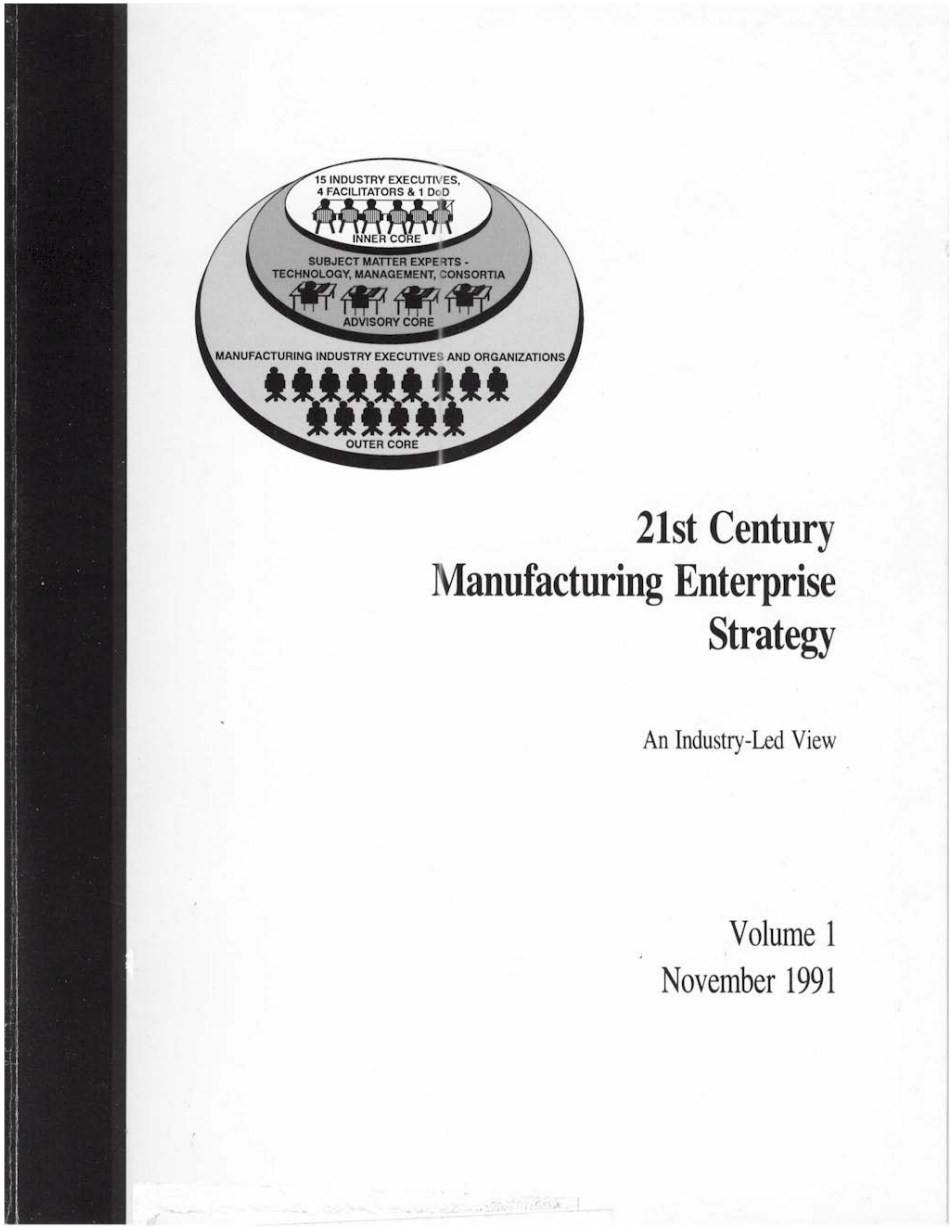

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21st Century Manufacturing Enterprise Strategy

An Industry-Led View

Key Points

- A new competitive environment for industrial products and services is emerging and is forcing a change in manufacturing.
- Competitive advantage in the new system will belong to agile manufacturing enterprises, capable of responding rapidly to demand for high quality, highly customized, products.
- Agility requires integrating flexible technologies of production with the skill base of a knowledgeable work force, and with flexible management structures that stimulate cooperative initiatives within and between firms.
- The Department of Defense has a vital role to play and has a large stake in the success of industry in making the transition to agile manufacturing.
- The standard of living Americans enjoy today is at risk unless a coordinated effort is made to enable U.S. industry to lead the transition to the new manufacturing system.

Volume 1

November 1991

This is Volume 1 of a report addressing the future of American industry. It has been written in response to the transformation of manufacturing practices that is currently in progress. Without the foresight provided by Charles Kimzey, Office of the Secretary of Defense Manufacturing Technology (MANTECH) Office and Steven Linder (Office of the Assistant Secretary of the Navy), this effort could not have been undertaken.

The report is the result of an industry-led consortium partially funded by the Office of the Secretary of Defense Manufacturing Technology (MANTECH) Program and facilitated by the Iacocca Institute at Lehigh University. The contracting office is the U.S. Navy MANTECH Office (Contract #N00014-91-C-0151). The participation of the consortium members was fully funded by their own companies, at a cost estimated to exceed $500,000. This included salaries over a three-month period, when at least half their time was committed to this project, as well as all travel and living expenses. It reflects a major commitment on the part of 13 corporations who contributed executives to the Inner Core, and almost 100 more who participated in two rounds of interaction with the ongoing work of the Inner Core.

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Acknowledgement

For the past six months, a dedicated team has devoted the majority of their energies to bringing this project to a conclusion. The report, in two volumes, represents the completion of the first stage in making America once again a leader in manufacturing. What happens now is in the hands of the great number of industry, government, and academic leaders who must take action to change the thinking in, and about, American manufacturing.

To make this project possible in the short time allotted was a feat that involved many dedicated individuals working as a team. Starting with the concept by Chuck Kimzey, Office of the Secretary of Defense MANTECH Program Office, and the direct guidance of Steve Linder and Leo Plonsky of the Navy MANTECH office, this project took root.

The report, with its hundreds of individual inputs, was organized primarily by Professor Steven Goldman and Professor Kenneth Preiss, for Volume 1 and Volume 2 respectively. Without the immense skill, intellect, and patience of these scholars, the report would not have the insight, nor the support, of the many individuals who made direct contributions.

Next we would like to comment on the stellar effort of the Inner Core team. These men and women worked double-time in fulfilling their "home office" commitments while attending over twenty working sessions in Bethlehem, Pennsylvania. The companies they represented, Air Products, AT&T, Boeing Helicopter, Chrysler, FMC, General Electric, General Motors, IBM, Kingsbury, Motorola, Texas Instruments, TRW, and Westinghouse, made a major contribution of both their executive's time away from their corporate business and the actual dollar cost of the travel and expenses.

Closer to home, the guidance of Lehigh University's President Peter Likins, Provost Alan Pense, Vice President Michael Bolton, and the Iacocca Institute's Executive Director, Laurence Hecht, was invaluable. They provided input and direction for the Inner Core team selection and objective development, as well as constructive comment of the final report.

Finally, as with all major projects, nothing could have been produced without the "behind the scenes" staff. Our research engineers, Orapong Thien-Ngern, Kumar Panicker, and Jorge Leon, teamed to provide endless literature research and technical support. The administrative staff led by Richard Neulight, Bill Jahn, and Joyce Barker oversaw the logistics, draft reports, project tracking and dissemination of information. Finally, the report itself reflected the full meanings of the Inner Core and the authors by the patient typing and formatting by all the project secretaries Robin Lapadula, Lee Hartranft, Veronica Turbedsky and Kathleen Dillon. The style of the finished product was enhanced by editor Len Estrin, illustrator Gene Mater, and designers John Saraceno and Carole Smith.

The total effort of the entire team reflects their attitude toward the project and the goal of providing a vision and the mechanisms to help make America once again a leader in global manufacturing. To all of them, a sincere thank you for the fine effort.

R.N. & R.D.
Co-principal Investigators
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Foreword

This is Volume 1 of a two-volume report on the global competitive environment U.S. manufacturing will face, and the infrastructure it will require, in order to compete as it moves over the next 15 years into the 21st century. The developments described in the report present a unique opportunity to capitalize on distinctive U.S. strengths; failure to seize this opportunity will put the standard of living of the American people at profound risk.

The report presents the thinking of leading representatives of industry, government and academe. It represents over 7500 man-hours of work and incorporates ideas culled from many excellent recent reports on U.S. industry. The distinctive value of this particular document lies in its presentation of a comprehensive picture of a new system of manufacturing-agile manufacturing-that has begun to emerge in the industrially advanced nations. Our objective in presenting this picture was to assist in defining a strategy and an action agenda that would enable U.S. industry to make the transition to this new system in a timely and competitively effective manner. Volume 1 of the report begins with a description of the opportunity for regaining global competitiveness that the transition to agile manufacturing offers American industry. It continues with a non-technical vision of agile manufacturing as a system in which technologies, management structures, and social values are synthesized into a powerful competitive weapon.

The opportunity and the vision chapters together provide the backdrop for four industrial scenarios. Each is written from the perspective of a successful agile manufacturing enterprise in the year 2006. Together, the scenarios identify the technological, managerial, and social infrastructures that will have to be put in place if such enterprises are to come into being. Volume 2 of the report amplifies the technical details implicit in the creation of these infrastructures.

The ultimate objective of this report is to provoke the actions that need to be taken now in order to restore the United States to world leadership in manufacturing. ***The fact that all of the world's leading manufacturers have to build a new infrastructure to make the transition from mass production to agile manufacturing provides a unique opportunity for U.S. industry to regain the leadership it lost in the 1970s and '80s***. Only a concerted effort, coordinated by industry, supported by the public, and with the cooperation of governmental and academic institutions can make this happen.

The vision presented here of the infrastructure required for creating agile manufacturing enterprises in the U.S. is, we believe, 80 to 90 percent correct. The key to making the vision come true, however, is not to make the vision 100 percent correct, but to immediately take steps to implement it. Refinement of the vision is best accomplished through the experience of working to make it a reality.

If the U.S. is to return to leadership in manufacturing, industry must take the lead in effecting that return. No single corporation, however, not even the manufacturing sector as a whole, can accomplish that task: it is simply too big a job. Only through inter-firm cooperation, and through cooperative, coordinated, efforts among industry, government and academe can that task be accomplished.

The key finding of this report is that there is a common infrastructure requirement for all agile manufacturing enterprises, regardless of their industrial sector. This common infrastructure will be used in different ways by different industries and different firms within the same industry. Consequently, companies and industries can work together to build the infrastructure, even while competing in the products and services it enables them to provide. The infrastructure will be used to tie production processes together and to integrate those production processes with other parts of the company, and with parts of different companies, into a single system. When the system functions efficiently, it allows companies to easily and quickly meet the needs of a rapidly changing competitive environment. In effect, the infrastructure will enable the formation of agile manufacturing enterprises, capable of responding to the fast-changing market needs and manufacturing demands of a global economy. We believe that competition in the 21st century will be dominated by agile enterprises. ***Those nations that focus now on speeding the transition to agile manufacturing will become the strongest competitors in the global marketplace***.

We have called our report a "21st Century Manufacturing Strategy". Accordingly, the Summary and Action Agendas section of this volume lays out steps that need to be taken: by industry; by the DoD, which has a vital stake in the success of industry; by Congress and the Executive Branch, which must act to protect the U.S. standard of living; and by academe, which must assume a more active role as an economic development agent.

Because of our concern that this not be just another report, we strongly recommend forming an Agile Manufacturing Forum. The objectives of this forum will be: to facilitate action; to maintain and build on the momentum generated by this project; and to provide a means for ongoing discussion and coordination between all those involved in carrying out the action agendas needed to develop the infrastructure.

After examining this report, we invite you to join us in turning the 21st Century Manufacturing Strategy into reality. The economic wellbeing and strength of America depend on it.

For the Inner Core Team
Roger N. Nagel & Rick Dove, Facilitators

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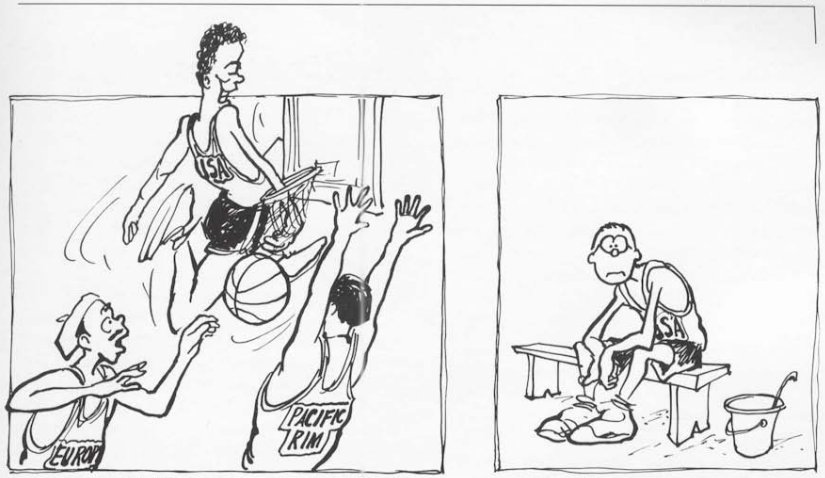
The Opportunity



DO YOU WANT TO SEIZE THE MOMENT...

...OR DO YOU WANT TO SIT IT OUT ON THE BENCH?

We stand at the threshold of a new era in manufacturing. Before us, an opportunity beckons to reverse a decade-long decline in American industrial competitiveness. If the opportunity is seized, the manufacturing sector of the U.S. economy will expand and a foundation will be laid for broadly distributed improvements in the quality of American life. Other nations stand beside us at that threshold, however. Japan is there and very soon South Korea will be. The thirteen member states of the European Community are in the process of uniting their national markets in order to establish a prominent competitive position for their own industries in the new era. These foreign competitors are already moving across the threshold. If the U.S. lingers, its manufacturing capability will soon be outdated, its competitiveness in domestic markets will continue to decline, and it will effectively be locked out of many world markets. A decline in the American standard of living is almost certain.

The implications for American society of the transformation of manufacturing that is underway are profound. Consider the following two capsule scenarios.

The year is 2006. The automotive Big Three are the No-Longer-So-Big Two and their partnerships with Japanese and Korean automakers account for the bulk of their domestic sales. Japanese and German robotics devices and numerically controlled machine tools dominate American manufacturing operations. Flat panel TV screens, a Japanese monopoly, have displaced the color picture tube. The booming market for bioengineering products is controlled by a joint Swiss-German-Japanese corporation with exclusive rights to the basic research they fund in hundreds of small U.S. commercial and academic laboratories. A Franco-German consortium has created a universal access, global information network, through which it has achieved dominance in computer networking, and in telecommunications, software and equipment. The U.S. economy continues to weaken from the chronic trade deficit and from the burden of a defense budget swollen by the need to maintain dedicated manufacturing facilities and large stockpiles of weapons designed for every projected mission requirement.

All too believable, given current trends?

The year is 2006 and the U.S. enjoys world leadership in manufacturing. Domestically, overall employment in manufacturing at both large and small companies has increased and industry profits are at record high levels. In the European Community, in developing countries around the world, and at home, U.S. companies compete aggressively for market share and are respected producers of quality goods and services. They have an especially strong position in leading edge computer

hardware and software, biotechnology, telecommunications, industrial process control equipment, and state-of-the-art consumer electronics products. The level of education of the U.S. work force is among the highest in the world. Management has long since integrated social concerns—environment, energy, work force structure, community impact—into the setting of company agendas, alongside technical and economic concerns. Maintaining U.S. military superiority requires a smaller fraction of the federal budget as DoD weapons requirements can quickly be met by commercial manufacturing facilities.

Unbelievable?

The very developments that today are driving the transformation of the mass production system of manufacturing can serve as a springboard for the U.S. to return to a leadership role in manufacturing by the year 2006. The technologies required by the new system are well defined and will become available, at a price, to whomever has the ability to use them. This ability, however, will depend upon innovations in the organization of manufacturing enterprises that may well favor the U.S.

Only a coordinated effort by industry, government, and the public can convert the present opportunity into a springboard for returning American manufacturing to global competitiveness.

American industry must acquire the necessary technologies in a timely manner, but the technologies alone are not enough. The technologies will have to be integrated into organizational frameworks that fully utilize the knowledge, creativity, and above all the initiative of the human resources available to industry. Even this is not enough. Industrial enterprises must have access to generic social resources — an appropriately educated work force, adequate communication and information networks, a supportive political, legal, and economic climate. Together, technologies, their organization within enterprises, and the linkages of these enterprises to their social contexts, constitute a system. New technologies and new organizational structures are today converging in a new manufacturing system, embodied in a new kind of manufacturing enterprise, agile enterprises.

Increasingly powerful information and communication technologies are being incorporated into the tools of manufacturing. Networks of computer-controlled production machinery are creating new kinds of industrial goods and services. In the process, a competitive environment is emerging in which the existing mass production system of manufacturing is at a disadvantage.

Where the mass production system achieved low unit costs by producing large quantities of uniform products, the new system achieves agility. It is capable of low unit costs while producing far smaller quantities of high quality, highly customized, products. In an agile enterprise, manufacturing machinery can be reprogrammed quickly to produce new products, in many variations. Products with a high information content, and related commercial services, are being created that will increasingly come to define the competitiveness of a nation's industrial apparatus.

In the mass production system, even with the enhancements of just-in-time and lean production, corporations attempted to do everything themselves. Competition favored large scale, comprehensive, operations. The agile manufacturing system favors smaller scale, modular production facilities, and cooperation between enterprises, each of which contributes a part to a new capability.

Agile manufacturing alters the meaning of industrial competition, as competitor, supplier, and customer firms occupy changing roles in relation to one another. Competition and cooperation become mutually compatible. In such a system, competitive advantage is determined by speed to market, by the ability to satisfy individual customer preferences, whether consumer or commercial customers, and by responsiveness to intensifying public concern about manufacturing's social and environmental impacts.

U.S.A.

In the United States, Japan, and western Europe a recognition is spreading that a new manufacturing system has already begun to take shape. A host of reports on the future of U.S. manufacturing implicitly or explicitly address the, as yet dimly perceived, outlines of that new system. The Departments of Defense and Commerce, the National Academies of Science and of Engineering, the White House Office of Science and Technology Policy, the Office of Technology Assessment, among other government bodies, have conducted inquiries into American manufacturing in order to assess its current and near-term adequacy to the challenges it is likely to face.

Private and public institutions, such as the Council on Competitiveness, the Boston Consulting Group, and the MIT Commission on Industrial Productivity, have issued reports on the strengths and weaknesses of American industry. They have recommended directions in which it needs to move if it is not to lose further ground, let alone regain its former strength.

Congress has become increasingly involved in what is now a decade-long public debate on the U.S. industrial competitiveness "crisis". It has passed legislation that:

- Enables the formation of certain kinds of consortia among competitors.
- Funds the consortial development of "pre-competitive" generic technologies and, in the case of Sematech, of competitive technologies.
- Encourages the commercialization of innovations developed with public funds.
- Accelerates the transfer of new technologies from the 700+ federal laboratories to private industry.

Many corporations and industrial organizations also have recognized that a transition to a new mode of manufacturing has begun. The rate of formation of consortia and of joint ventures—among private firms, and between firms and government agencies, most notably the DoD—has accelerated sharply in the past decade. CAM-I (Computer Aided Manufacturing - International), Sematech, NCMS (National Center for Manufacturing Sciences), MCC (Microelectronics and Computer Technology Corp.), GLCC (Great Lakes Composites Consortium), to name just a few, reflect an awareness that only a cooperative effort can manage this transition successfully. The knowledge base necessary to effect the transition is beyond the capability of any one company to generate on its own.

Such highly publicized recent joint ventures as those of GM, Ford and Chrysler, of IBM, Motorola and Apple, and of IBM and Siemens are symptomatic of initial responses to a recognition that innovative measures are called for to remain competitive in the new industrial environment. Business as usual is unlikely to succeed for much longer.

Europe

In western Europe, concern over competitiveness in a new global manufacturing environment has precipitated an unprecedented subordination of national prerogatives to regional unification. The 1992 Single Market Act of the European Community was promoted by virtually all leading industrialists and politicians, and supported by a large public majority, on pragmatic grounds. They acted on the conviction that, divided, the national markets of the EC member states could not withstand the competitive pressure that Japanese and U.S. manufacturing, employing new production technologies, would soon be bringing to bear on them. United, however, they had a chance to achieve at least competitive equality, by jointly reconstructing a common manufacturing system employing those same technologies.

The political price these countries have indicated they are willing to pay to avoid industrial obsolescence is a sign of how seriously those communities take the imminence of a new era in manufacturing. The unification initiative in its current form was formulated in 1985, in an EC "white paper". In less than five years, all of the difficult, and once implemented largely irreversible, decisions necessary to achieve market unification had been taken. In addition, the EC nations began at once a series of generously funded, transnational consortia to develop state-of-the-art competence in a range of leading edge manufacturing technologies cooperatively: EUREKA, BRITE, JESSI, ESPRIT, and RACE.

After announcing joint ventures with Siemens AG to produce new chips, and with Lotus and Wang to develop software and office computing products, IBM signed an agreement with Apple Computers to create a jointly owned software company. The new company is to develop an operating system for a series of IBM and Apple computers that will be fully software compatible. The computers will use the same central processor, a modified version of the one in the IBM RS/6000 workstation. It will be manufactured by Motorola, exclusive supplier of processors for Apple Macintosh computers since their introduction, with IBM assistance in the redesign. Part of IBM's contribution to the new operating system will come from yet another of its joint ventures, called Patriot Partners.

In addition, Apple and IBM will work together to develop a means of allowing software written for Macintosh computers to run under the AT&T-developed Unix operating system used on IBM workstations. Each company is free to offer the other's product line to its corporate customers, and Apple can introduce IBM compatibility into its own computers as quickly as it chooses do so.

[Sources: Wall Street Journal, 7/5/91; NY Times, 7/4/91]

GM and Toyota have a joint manufacturing venture in Fremont, California, New United Motor Manufacturing Incorporated, at which GM's Geo Prizm cars are made. Chrysler and Mitsubishi have a joint manufacturing venture, Diamond Motors, in Normal, Illinois, at which Chrysler Eagle Talons/Plymouth Lasers and Mitsubishi Eclipses are manufactured. Ford and Mazda are engaged in a number of collaborative manufacturing ventures, reflecting Ford's 25% equity position in Mazda: the Ford Probe model is manufactured by Mazda, the Ford Escort is largely a Mazda design modified by Ford engineers in detail, and the two companies jointly produce Ford Probe and Taurus Models in Japan.

GM, Ford and Chrysler also have joint ventures with one another, among them: A transmission manufacturing facility; a company to develop advanced storage batteries, primarily for electrically-powered cars; and a plastics forming company.

EUREKA:

European Research Coordination Agency. Its 1988 budget was $5 billion supporting 165 cooperative high-technology R&D projects involving 600 companies in 16 European nations.

ESPRIT:

European Strategic Program for Research and Development in Information Technologies. Started by the European Community in 1984, in 1990 it supported 5500 researchers in the 13 EC member nations.

JESSI:

Joint European Semiconductor Silicon Initiative. A $4 billion funding pool was created by a consortium of governments and private industry, each group contributing half of the money.

In 1990, JESSI and Sematech agreed to create common semiconductor research data bases.

BRITE:

Basic Research in Industrial Technologies for Europe.

RACE:

Research & Development in Advanced Communications Technologies in Europe.

Japan

The Japanese have since 1986 been engaged in an exercise whose objective is articulating the next mode of manufacturing, the one that comes after mass production. They have identified the strengths and the weaknesses of the manufacturing system that has been the vehicle of their rise to a prosperity and international economic power unparalleled in their history. But the limits of this system have been reached, for them.

Quality control and just-in-time inventory management have done as much as they can do. More importantly, they are doing the same things for other manufacturing nations; not just for a resurgent U.S. and a newly dynamic western Europe, but for East Asian rivals as well. In fact, the mass production system has reached such a degree of sophistication, its managerial and technological structures are now so robust, that it can be installed virtually anywhere in the world. Wherever some natural, social, or political factor creates a competitive advantage, a factory can be located. Quality alone cannot make enough of a difference to keep the manufacture of standard products, using mature technologies of production, an attractive investment in developed societies for much longer.

Already the Japanese see signs of decline in the functionality of the current system of manufacturing. The number of young Japanese engineers going into industry is dropping. Of those that go into industry, the number going into manufacturing is also dropping. Young Japanese, having grown up in a prosperous and peaceful society, are not displaying the devotion to work, or the company loyalty, that characterized their parents' generation. Increasingly, the Japanese public is taking up the concerns about the environmental and social impacts of industry that have been prominent in the U.S., Canada, and western Europe since the late 1960s.

At the same time, a consensus has taken shape among Japanese industrialists about a new manufacturing system, one that will complement mass production, not replace it, and be profitable even in Japan. There are problems with this system, too, the least of which are technological. The new system will depend on spontaneous work force initiative and on innovative creativity at the operational level of an enterprise. Neither of these have been noteworthy characteristics of Japanese industrialization, or society. The system will depend on distributed authority and globally decentralized manufacturing facilities, but the Japanese have had difficulty treating other nationals as peers. Both at home and abroad, Japanese managers will have to deal with women who will merit, and expect, promotion to positions of authority, yet another problem for Japanese culture. Finally, the successful implementation of the new technologies will be critically dependent on the software linking human workers at all levels with a national information network capable of controlling manufacturing operations. Software development has not been a strength of the Japanese computer industry to date.

Japanese corporations nevertheless have already begun to explore the potential of the latest manufacturing technologies for rapid product development, for offering multiple models of basic designs with many customization options, and for profitable production of relatively small product lot sizes. The Mazda Miata facility, which is profitable at 40,000 vehicles per year, is one illustration of a successful outcome of these explorations. It is neither the only one, nor the last.

The Charge of this Project

The 21st Century Manufacturing Enterprise Strategy Project built on recent studies whose common objective was identifying the nature and the requirements of the emerging new manufacturing system.

Project activities were guided by the following principles:

(1) The range, and the intensity, of these earlier efforts, and the convergence of expert opinion they embody, testify to the reality of the new manufacturing system they each anticipate.

In 1987, representatives of ten Japanese industries began a five-year project to discuss the future of Japanese manufacturing. Initially a research study of the System Science Institute of Waseda University sponsored by the Japan Machinery Foundation, the participating companies subsequently provided the funding. MITI was not involved at any level.

As the project proceeded, it drew in widening circles of industrial participants and has achieved considerable visibility in the Japanese management community. Its focus has been on barriers to implementing a new, post-mass production, manufacturing system. A central theme has been a theory of the integration of autonomous dispersed units into coherent wholes (holonics).

[Source: Robert Hall, *Manufacturing 21*, AME]

In 1989, MITI launched an initiative to push the development of Intelligent Manufacturing Systems (IMS) as a core technology of post-mass production manufacturing. By 1991, MITI had created a consortium of 80+ Japanese firms.

In 1990, the Japanese invited U.S., and later western European, participation in a joint effort to develop a common specification for intelligent manufacturing control systems hardware and software. The European response has been orchestrated through ESPRIT. After an initial period of confusion, the Department of Commerce, aided by an Ad Hoc Industry Committee, is representing the U.S. position in ongoing tri-lateral negotiations.

(2) Because of this convergence of opinion, it is possible to amalgamate from the many earlier studies a common vision of the agile manufacturing system that is coming into being. Doing so provides a more detailed, and a more comprehensive, view of the structural features of that system than any one group has formulated to date. This was the Project's first order of business.

(3) The increasing tempo of private and public studies of manufacturing, and the widening constituencies they are attracting, indicate that the time is right for coordinated action to shape the transformation of manufacturing to U.S. national advantage. Recommending courses of action appropriate to the various institutions that must support the transition to agile manufacturing became the Project's next order of business.

(4) A compelling case can be made that the transition to agile manufacturing will require sustained cooperative, as well as coordinated, effort among industrial enterprises, and between them and government agencies. The time is right for identifying effective mechanisms for such cooperation and for activating them by funding appropriate cooperative projects.

(5) Prophecy is sometimes dangerous, but always imprecise. It will, therefore, be necessary to create a framework for regularly monitoring, and suitably adjusting, the mechanisms for cooperation, and the projects funded under them, to reflect evolving competitive realities. This defined the Project's final objective.

A U.S. Springboard

If American firms have access to the required technologies, their synthesis into an agile manufacturing system will be dependent on:

- Managing a multi-cultural and gender "blind" work force.
- Managing an organization whose dynamic ability depends on spontaneous initiative at all levels of management.
- Developing a "culture" of continuous creativity and initiative at operational levels of the workplace.
- Routinely forming multi-enterprise ventures, enabled by the removal of social and legal obstacles to cooperation.
- Developing software that will allow humans, computers, and production machines to interact easily enough for computers to realize the full potential of the agile manufacturing system.
- Attracting into manufacturing intelligent young people who desire professionally challenging careers.

In its global operations, U.S. industry has an established record for respecting and rewarding the abilities of local personnel in its foreign operations. This includes their promotion to the highest managerial positions in U.S.-owned foreign operations. American society has moved steadily, over the past twenty years, towards eliminating the disparity between workplace treatment of men and women. The promotion of women to positions of authority in industry has become a familiar, though not yet a routine, phenomenon for U.S. companies. Entrepreneurial initiative and technical creativity have been hallmarks of American industry for over 150 years. Software development is one of the technologies in which America holds a commanding world leadership position.

More generally, the U.S. is a world leader in information science. It also possesses a diverse supplier base that constitutes a major resource for cooperative ventures in an

Apple Computer, Becton Dickinson, Cypress Semiconductor, and Xerox are among a growing number of companies that are actively encouraging their employees to form self-organized, self-directed project teams. The idea is for management to facilitate work force initiative and creativity rather than to dictate courses of action. Innovation and an entrepreneurial spirit are believed to be widely distributed American virtues, but traditional managerial hierarchies tend to strangle both, except for a chosen few.

For the past six years, the FMC Naval Systems Division plant in Aberdeen, South Dakota, has been operating exclusively under a system of self-directed, self-managed work teams. In August, 1991, the facility received the first perfect incentive fee score awarded in the eight-year history of the U.S. Navy Standard Missile/Vertical Launching Systems Program. The welders and assembly line workers were cited for "zero quality defects for [Tomahawk missile] canister deliveries and accelerated production [to meet Persian Gulf War needs.]"

[Source: Aberdeen American News, 8/9/91.]

Self-forming project teams pose their own managerial headaches. Cypress has a computer program that keeps track of what each of its 1500 employees are doing at any given time. Apple has a program that allows a manager to identify who in the company has the skills that would fit into a new project and, if they are available and interested, to add them to the team. Under the best of circumstances, management needs to play a complex coordinating role and to assign priorities and allocate resources in accordance with some "big picture" of the firm's best interest.

Nevertheless, for companies in industries in which competitiveness is determined by continuous innovation, rapid new product development, and product design and performance, unleashing the knowledge contained in the total work force can be a powerful strategic weapon. It is also perhaps the best way to achieve the flexibility necessary to remain competitive. Such self-organized, self-directed teams show the best promise for escaping the not—invented-here-syndrome and forming alliances with units of other companies. Because they are narrowly focused on getting some particular job done as well as possible, project teams formed at their own initiative reach out for the best help they can find. Apple, Nike, IBM, and GE are among many firms who have embraced the tactic of farming out parts of projects to companies that possess some relevant expertise that they would have to develop.

[Source: Fortune, 6/17/91]

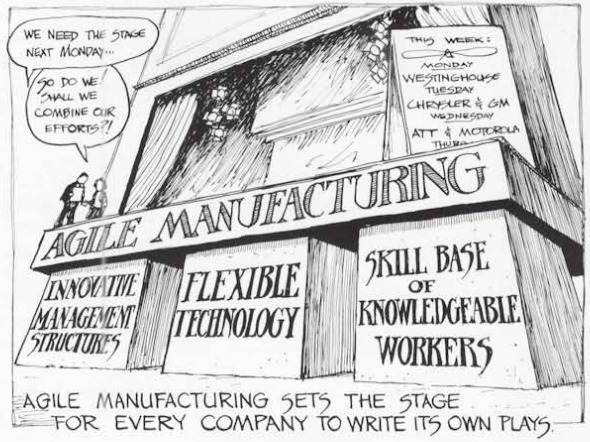
agile manufacturing environment. Linking these two could create a significant competitive advantage for U.S. industry.

Attracting a larger number of intelligent, creative young people into manufacturing than now choose such careers is a problem that U.S. and Japanese industry share. The "pipeline" into science and engineering careers has received considerable attention in recent years. It remains poorly understood and, after reaching the highest levels in U.S. history in the early 1980s, undergraduate engineering enrollment has been declining since 1986. The number of women entering the engineering profession had increased ten-fold between 1970 and 1986, but it has since levelled off, at about twelve percent of first degree recipients. Minority engineering enrollment over the same period doubled and it, too, has levelled off. Apart from quantity and diversity issues, American science and engineering educators need to identify the distinctive requirements of agile manufacturing for technical professionals and to reform undergraduate and graduate curricula to satisfy those requirements.

A growing number of American companies (e. g. Apple, Becton, Dickinson, Cypress Semiconductor and Xerox) have already begun to experiment with inverting the pyramid of managerial authority to permit the formation, and to allow the execution, of new project initiatives "from below". It will be necessary to exploit the flexibility and the rapid response capabilities of the new production technologies. This is an established Japanese strength. To excel at multi-disciplinary teamwork, Americans will have to overcome the national prejudice for "going it alone", for valuing individual achievement above team achievement: the "Lone Ranger" syndrome. On balance, however, the transition to a system of manufacturing with these infra-structure requirements gives the U.S. a clear opportunity to build on its strengths.

Crossing the Threshold: A Vision of the Agile Manufacturing Enterprise

The agile manufacturing enterprise is able to bring out totally new products quickly. It assimilates field experience and technological innovations easily, continually modifying its product offerings to incorporate them. Its products are designed to evolve. As the needs of users change, as improvements are introduced, users can readily reconfigure or upgrade what they have bought instead of replacing it. Reprogrammable, reconfigurable, continuously changeable production systems, integrated into a new, information intensive, manufacturing system, make the lot size of an order irrelevant. The cost of production is the same for 10,000 units of one model, as for one unit each of 10,000 different configurations of all of the models of a single product. Agile manufacturing thus produces to order, where mass production manufacturing produced to stock and sell, basing its production schedule on marketing projections. Similarly quality in agile manufacturing advances from being measured in defects per part when sold, to customer gratification over the full life of the product.



Because of the longevity of its evolutionary product lines, the agile manufacturing enterprise develops strategic relationships with its consumer, as well as with its commercial, customers. In place of the sale-and-limited- warranty relationship, it offers customers a continuously variable mix of products, services, and value-adding information. To facilitate this relationship, it communicates with its products while they are in their users' possession. Information is exchanged, software upgraded, diagnostic servicing performed, and individual product histories maintained. Customer confidence is maintained over long product lifetimes by continuous investment in the skill base of the agile enterprise's work force, which is valued as the enterprise's central long-term asset. The work force is responsible for innovative product evolution and for manufacturing process improvements that allow cost increases to be recovered internally, rather than through price increases.

Mass production enterprises are operationally focused and emphasize short-term financial performance. Because of the limited flexibility of their production technologies, they extend the status quo as long as possible in order to amortize sunk costs. Agile enterprises are strategically focused, and emphasize long-term financial performance. They see opportunities for growth and profit in constant change, which their production technologies and managerial organization, both highly flexible, are able to exploit. Authority is diffused in the agile enterprise, not concentrated in a chain of command. Instead of a static corporate structure based on fixed, specialized, departments, agile corporations have a dynamic structure, keyed to the evolving needs of cross-functional project teams. Where technology, under the mass production system, is perceived as the key to solving manufacturing and marketing problems, under agile manufacturing people, optimally utilizing technology, are the problem solvers.

The agile enterprise is the natural next development of industry. The modern corporation created in the 1880s integrated relatively inflexible production machinery, a largely illiterate work force, and an international network of technological innovations in communication and transportation, into a centrally administered, hierarchically ordered, managerial structure of great power. Local manufacturers in industry after industry succumbed to the competitive advantages of centralized mass production and national distribution. Except for high quality, customized, niche markets, companies that did not emulate the modern corporation could not compete with it for long. It has prospered through 100 years of revolutionary social, political, and technological change, but it is being challenged today.

Agility is accomplished by integrating three resources: technology, management, work force, into a coordinated, interdependent, system. Highly flexible production machinery is a necessary condition for the emergence of agile manufacturing enterprises, but it is not sufficient by itself to bring them about. The required production technologies are either already here, in embryonic form, or are foreseeable: flexible, programmable machine tools group in reconfigurable, modular, and scalable manufacturing cells; "intelligent" manufacturing process controllers; closed loop monitoring of manufacturing processes employing sensors, samplers, and analyzers coupled to intelligent diagnostic software; the computer power, and the manufacturing process knowledge base, to design complex products digitally, to simulate their properties and behaviors reliably, and to model the processes of their manufacture accurately. Achieving short product cycle times—the rapid creation, development, and manufacture of new products—requires linking these technologies to organizational structures that can fully exploit their power.

Agile manufacturing enterprises employ a dynamic, and organizationally comprehensive, planning style.

- Setting bold goals that create enterprise-wide challenges.
- Opening the strategic planning process to all levels of the enterprise.
- Leveraging existing resources to meet goals out of proportion to current capabilities.
- Evoking personal commitment to long-term goals from everyone in the enterprise.
- Creating a climate of reciprocal responsibility for the success of the enterprise.
- Encouraging creativity and initiative by identifying goals clearly, but remaining vague about means.
- Providing the work force with the skills and the tools they need to achieve the goals.
- Monitoring progress towards goals anticipating evolutionary changes in direction.

[Source: Gary Hamel, C.K. Prahalad, Harvard Business Review, May-June, 1989]

Production Technologies

Agile enterprises are totally integrated organizations. Information flows seamlessly among manufacturing, engineering, marketing, purchasing, finance, inventory, sales, and research departments. Work proceeds concurrently rather than sequentially. The development of new products and the development of the processes for manufacturing and marketing them take place concurrently. Design is not the province of engineering, not even of engineering and manufacturing jointly. Instead, representatives of every stage in a product's life cycle, from materials employed in its manufacture to its ultimate disposal, participate in setting its design specification. Information thus flows seamlessly between agile manufacturers and their suppliers, too, as well as between manufacturers and their customers, who play an active role in product design and development under agile manufacturing. Every product can be dealt with on a highly interactive network. Physically dispersed and organizationally segregated personnel from the same company can work collaboratively with one another and with personnel distributed across other companies.

Distributed enterprise integration, and distributed operational concurrency, are made possible by strict, universal, data exchange standards, by robust "groupware"—software allowing many people to work on the same files at the same time,—and by broadband communication channels capable of carrying the amount of information involved in these exchanges. The synthesis of these into off-the-shelf enterprise integration software and hardware - analogous to the emergence of off-the-shelf computer networking technologies in the late 1980s-will signal the onset of the agile manufacturing era. With reliable integration technologies, safe large-scale software changes that do not disrupt system operations will become routine.

Enterprise integration is also made possible by an atmosphere of mutual responsibility for success, within enterprises and between cooperating enterprises. The ethics of agile manufacturing will be mutual trust, based on the need to make cooperation a first-choice approach to problem solving, and sharing relevant information with all project collaborators. Trust and mutual responsibility require a capacity for localized decision making that is a major determinant of agility. Agile enterprises can make and implement many decisions at the point of information. They do not have to wait for requests to move up and then back down the organizational hierarchy before acting. Issues locally decideable include: production scheduling changes, error detection and response, cooperation with other units of the enterprise in setting and pursuing shared goals, and changing pathways to those goals when problems arise.

Managerial Techniques

The ultimate expression of trust, given the proprietary attitudes towards information that prevail today, is the routine formation

Many of the features projected as characteristics of agile manufacturing are already discernible, at least in early stages of development, in the continuous process industry. Among these:

- The formation of virtual companies, enabled by information exchangeability.
- Modular, "plug compatible" organizational structures and production facilities.
- Networks of alliances among suppliers, producers, and customers characterized by close cooperation.
- Shared production capabilities and (to a lesser extent) shared production facilities.
- Pursuit of absolute process control through closed loop monitoring, real-time sampling and analysis, and diagnostics software built into sensors.
- Direct feedback of sales and customer use information into production decision processes.
- Increasingly intensive computer modeling of processes with a view to eliminating pilot plants.
- Research into computer simulation of reaction kinetics with the objective of "designer" chemicals.
- A central role for manufacturing in corporate planning and in engineering.
- Manufacturing research directly linked to "basic" R&D.

of "virtual" companies by groups of agile manufacturing enterprises. Speed to market with complex new products is a major competitive advantage. Often, the quickest route to the introduction of a new product is selecting organizational resources from different companies and then synthesizing them into a single, electronic, business entity: a virtual company. If the various distributed resources, human and physical, are "plug compatible" with one another, that is, if they can perform their respective functions jointly, then the virtual company can behave as if it were a single company dedicated to one particular project. For as long as the market opportunity lasts, the virtual company continues in existence; when the opportunity passes, the company dissolves and its personnel turn to other projects.

The ability to form virtual companies routinely is a powerful competitive weapon. It exploits a number of distinctive American strengths, notably, world leadership in information science and a vast, diversified supplier base. Having achieved distributed enterprise integration, agile manufacturing enterprises routinely form virtual companies. The medium they use is a national industrial network, a Factory America Network (FAN). FAN combines a comprehensive industrial data base with services that allow groups of companies to create and operate proprietary virtual entities. Its operation assumes the removal of legal barriers to multi-enterprise collaboration and the creation of standard consortium formation models that make forming a virtual company as straightforward as making a will or forming a corporation.

Corporate perceptions that going it alone is better than cooperating need to be overcome, as do organizational obstacles to working cooperatively with other companies as a first, rather than as a last, resort. Intellectual property rights issues generated by collaborative ventures need to be resolved. Techniques need to be developed for managing companies that promote work force initiative at the operational level, as well as performance measures for self-directed, inter-enterprise, project teams. These are formidable tasks. The alternative, however, is repeatedly showing up in the marketplace with too little, too late.

Agility is becoming a condition of survival. An intensely competitive environment for advanced industrial goods and services has already begun to take shape. Markets are fragmenting and changing rapidly as a steady flow of new products appear in a wide range of continually changing models. Stimulated by the variety of models available, commercial customers and consumers alike are becoming more demanding. They want to buy high quality, low cost, high performance products configured with just the features they feel they need. Performance and cost remain objective measures, but the meaning of "quality" is changing. Quality as reliability, which is an objective attribute of a product, no longer confers competitive advantage. Consumers are learning to take reliability for granted. Quality is coming to mean satisfaction, the subjective response of a customer to owning and using a product.

At the same time, more and more products are being designed to compete in highly diversified global markets. Their design, manufacture, distribution, and servicing are being managed by transnational corporations using globally distributed assets and resources. Increasingly, manufacturing companies are being required to satisfy locally imposed constraints reflecting environmental, safety and energy efficiency concerns as well as social, political and economic values. In such an environment, classical forms of vertical integration, attempting to do everything "in house", are a recipe for failure.

An agile enterprise has the organizational flexibility to adopt for each project the managerial vehicle that will yield the greatest competitive advantage. Sometimes this will take the form of an internal cross-functional project team with participation by suppliers and customers. Sometimes it will take the form of collaborative ventures with other companies, and sometimes it will take the form of a virtual company. The guiding principle of agile enterprise management is not automatic recourse to self-

directed work teams or to virtual companies, but full utilization of corporate assets. In a dynamic competitive environment, the key to utilizing assets fully is the work force. Flexible production technologies and flexible management enable the work force of agile manufacturing enterprises to implement the innovations they generate. There can be no algorithm for the conduct of such an enterprise. The only possible long-term agenda is providing physical and organizational resources in support of the creativity and initiative of the work force.

Knowledgeable Work Force

It is a cliche that technological innovation is unpredictable. In the agile manufacturing era, constant innovation in the creation and evolution of products and services, and in the improvement of manufacturing processes, is synonymous with competitive advantage. Agile manufacturing enterprises are able to manage unpredictability by maximizing the scope for human initiative. A knowledgeable work force, expected to display initiative and provided with the means to exercise it, is the single greatest asset of such an enterprise. Continuous work force education and continuous growth in the quality of the work force are therefore long-term investments aggressively pursued by management. The better able every employee is to assimilate information and to respond creatively to new possibilities suggested by it, the more successful the enterprise. This is as true of managers and production line workers as of technical professionals. The involvement of scientists and engineers in strategic planning, as well as in operational activities, is crucial to the agile enterprise. Scientific knowledge of the manufacturing process, and coordination of engineering expertise with all phases of product creation and development, are central resources.

Everyone in an agile enterprise needs to understand that flexibility transforms the enterprise into a general purpose tool, one whose applications are only determined (and are only limited) by the imaginations of those working with it. Mass production enterprises, with their dedicated manufacturing facilities, are special purpose tools. The limiting factor in mass production is the fixed nature of the manufacturing systems. The agile enterprise, by contrast, has continuously evolving manufacturing systems. The capabilities of the agile manufacturing system are limited only by the imagination, creativity, and skills of the work force, not by equipment.

These characteristics of the agile manufacturing enterprise dictate attitudes toward managing the work force very different from those prevailing in mass production enterprises. Adversarial relationships between management and employees are insupportable, as are policies of limited access to information about the enterprise and its operations. Information must be open to an unprecedented degree, entailing an atmosphere of trust and of mutual stakeholder relationships. The workplace must not only be safe, but positively attractive to intelligent, creative people at every level of the enterprise.

Expectations of high levels of employee involvement must be created, sustained, and rewarded, again, at every level, from production line workers to executives. Routine creation of cross-functional project teams and virtual companies pose additional managerial challenges. Elitist organizational values are incompatible with the egalitarian character of project teams. Parochial managerial attitudes, privileging the accomplishments of one's "own" participants in an inter-enterprise collaboration, are incompatible with "best effort" commitments to such collaborations. A new kind of "social contract" between employer and employee is called for. The employee must be tied to the company through mutually perceived long-term benefits that anchor their loyalty in the face of routine participation in projects outside the boundaries of the company as traditionally conceived.

Implications For Society

The evolving relationship of U.S. industry to the U.S. economy is similar to the relationship of U.S. agriculture to the economy. Over the past century, agricultural employment has fallen from 60 percent of the total work force to 3 percent, with the bulk of production coming from only a small fraction of that 3 percent. At the same time, American agriculture's extraordinary productivity is a major contributor to the standard of living Americans enjoy, through low food prices, and plentiful and highly varied food supplies. Furthermore, while direct farm labor has shrunk almost to insignificance as a factor in employment, employment in the total food production and supply system, extending over farm machinery, chemicals and services, food processing, new product development, research, distribution, packaging, advertising, marketing, and sales, continues to increase.

Just so, production line labor, even with a resurgent U.S. manufacturing capability, will continue its slow, long-term decline from its peak in the late 1940s. Today, manufacturing employment accounts for approximately 17 percent of the U.S. work force. Even as that figure declines further, total employment in the agile manufacturing system will grow, as personnel are added to the manufacturing enterprise apparatus

within which agile production operations are embedded. In addition, the quality of all agile manufacturing jobs, including those in production, will be enhanced by the premium placed on initiative, knowledge, and active involvement by all levels of the manufacturing organization in setting and executing production agendas. Furthermore, as with agriculture, the productivity of agile manufacturing will be central to the quality of American life, through the kinds of customer-focused products it will provide and through the value of goods and services that it will contribute to the American economy. A competitive manufacturing system will make a balanced trade account possible; and an agile manufacturing system, developed in coordination with DoD needs, will permit significant savings in the defense procurement budget while retaining military leadership.

It is the overall system, not its individual elements, that generates wealth for society, that creates resources and opportunities, and affects social institutions, practices, and values. It is a serious mistake, therefore, to infer from declining blue collar employment the decreasing significance of manufacturing to America's future prosperity. Such an inference ignores the fact that production operations are always embedded in a manufacturing system with a wide range of social ramifications. That was true of mass production. It was also true of the earlier craft-based production systems. It will be true of agile manufacturing as well. The requirement of a more knowledgeable work force under agile manufacturing than satisfied the needs of mass production has important implications for education. Mass production factory workers tended inflexible machines. The work was commonly routine, repetitive, required little initiative or understanding, either of the particular job being done or of the wider production scheme into which each job fit. Agile manufacturing, on the other hand, requires that every worker understands the production scheme into which their jobs fit, that each displays initiative and is routinely capable of changing what they do and the way they do it.

Agile manufacturing requires that managers, too, understand the production system's operation and the relationship of its capabilities to setting managerial agendas. The gulf that opened between manufacturing and strategic planning in American industrial corporations from the 1960s through the mid-1980s must be bridged, in part through changes in business and management education. Technical professionals, too, must function differently in an agile, than in a mass production, manufacturing environment. Science and engineering education must provide its graduates with the knowledge and the skills they need to function in an atmosphere of continuous innovation, rapid reorganization of personnel and resources into multi-functional project teams, and highly interactive determinations of how to utilize constantly expanding technical knowledge.

At GM of Germany's Opel division, involvement of production workers in a corporate reorganization in the mid-1980s led to their approval of Saturday shifts and the use of outside suppliers when demand for Vectra and Omega models soared. As a result, Opel profits in 1989 jumped to a record $598 million and it moved into second place in the German car market. Such mutual stakeholder relationships between labor and management are a prominent characteristic of post-WW II German industry. Production line employees who demonstrate ability are regularly promoted to executive positions, and managers are evaluated on their success in advancing the careers of subordinates.

[Source: Fortune, 4/22/91]

CP Industries, McKeesport, Pennsylvania, is a steel products manufacturer housed in a former U.S. Steel plant bought by its managers in 1986. The new owners implemented a bold participative management system that has resulted in steady growth, and increasing profitability. All hiring is done by the workers themselves, through a fifteen member committee. There are no time clocks to punch and all workers are reimbursed in full for tuition paid to study any subject, whether job-related or not. Each new hire is given a three-day orientation and assigned to a mentor until they are fully integrated into the work force. Management's next step is self-directed work teams.

[Source: Phil. Inq. 6/22/91]

If competitive pressures are "pulling" a transformation of manufacturing into existence, it is also the case that social pressures are driving manufacturing in the same direction. Environmental concerns are the most obvious source of pressure, ranging from anxiety over the global impact of manufacturing to local pollution issues. Energy concerns, natural resource depletion, manufacturing workplace safety, and the social impact of manufacturing are drivers second in visibility only to environmental ones. The posture of industrial management toward these manufacturing-related social issues has, until recently, been reactive, treating them as negative externalities to be coped with as they arose. The implementation of a new manufacturing system, more explicitly coupled to a broad range of social institutions and values than mass production manufacturing was, offers an opportunity to adopt a new, proactive, posture.

In an agile manufacturing environment, it is natural for management to assimilate into the managerial decision-making process the total impact of manufacturing. The concept of manufacturing expands from a narrow focus on production of consumable/disposable goods to the comprehensive process of

creating, developing, selling and maintaining products over their entire life cycles, which for many products will be highly extended by reconfiguration and upgrade capabilities. With this expansion comes a complex set of interdependencies among manufacturers, suppliers, customers, and public institutions that make it advantageous for manufacturers to internalize social drivers, rather than have them constrain manufacturing from the outside, for example, from political responses to special interest activism.

The rise to dominance of the mass production system threatened the extinction of small producers who could not, or would not, adopt the production technologies or the managerial structure of the new corporations. The emergence of agile manufacturing, by contrast, enhances opportunities for small businesses through the wider access to their services that a national manufacturing network would allow. The routine formation of virtual companies, as well as of smaller scale electronic alliances, diminishes the attractiveness of single enterprise vertical alliances. The complex of small suppliers, machine shops, and specialty manufacturers that is an internationally acknowledged strength of American industry can in this way be knit into a new national resource. Doing so will require equal access to comprehensive coverage, broadband, communication channels, and the creation of a national industrial data base, with uniform data exchange standards for sharing digital engineering drawings and 3-dimensional parts descriptions.

If an agile manufacturing system is to be implemented, many currently held "truths" need to be unlearned, among them, that cooperation is less desirable than succeeding on one's own; that labor management relations must be adversarial; that information is power and can be shared only to one's detriment; that trust makes one vulnerable; that there are single technological solutions to complex problems; that breakthroughs are the only targets worth aiming at; that markets will appear by themselves once better mousetraps are invented; that infrastructure requirements will take care of themselves once pioneers have thrown up superstructures; that standards are constraining and their formulation dull work; that only parts can be invented, not whole systems.

The task of effecting the transition to a new era in manufacturing is a social task, though one that must be led by industry if it is to be accomplished at all. It cannot, however, be accomplished solely by industry. The transition must be led by industry because only through experience in the new competitive arenas can the requirements of the agile manufacturing system be identified and the effectiveness of mechanisms for meeting them evaluated. Nevertheless, society is a mutual stakeholder in effecting the transition along with industry. Not only is it the case that the one cannot prosper without the other, but both must make investments in a production system that will cause each to be transformed.

This is obvious in the case of industry, but society, too, must anticipate changes in social institutions and in social and personal values. The rise of mass production manufacturing profoundly affected all of the societies that adopted that mode of industrialization. The imposition of compulsory public education, the urbanization of populations, the ways people lived, worked, and played, the financial, commercial, legal and political structures of industrial life, were all influenced to a greater or lesser degree by the implementation of mass production manufacturing as conducted by modern corporations. The rise of agile manufacturing will exert an analogous social influence. Some of the changes that will take place can be foreseen, at least in part, because they will be deliberate. These are discussed in various places in this report. Some of the changes, perhaps the most profound, cannot be foreseen. The option of inaction, however, will cause no less profound, and equally unforeseeable, social changes. With inaction, the competitiveness of U.S. industry will decline. The American economy will adjust by reacting to initiatives of others, rather than by itself setting the agenda for a new set of international relationships with more competitive rivals.

With the experience of the Industrial Revolution behind us as a sobering lesson, the course of wisdom is to move into the industrial future open to learning lessons as far in advance of their social or environmental impact as possible. For that, vision is essential, in order to be able to relate where we are to where we want to be. But formulating a vision without taking action is as sterile as is taking action without first formulating a vision. The ideal is a vision that stimulates action appropriate to its realization.

Scenarios From 2006

The following four scenarios highlight selected features of advanced manufacturing after its transformation from the mass production system to an agile, customer preference-driven, system. These features are incorporated into narratives written from the perspective of 2006 and focusing on four industries: automotive, chemical, consumer electronics, and semiconductors. The scenarios were written from a non-specialist executive point of view. The objective in writing them was to depict the elements of an agile manufacturing system as they might function in practice.

The focus of the scenarios is on the manufacturing process, broadly conceived. Particular products or technologies were used only as means to the end of illuminating infrastructure features of the agile manufacturing process. It is clear that many of the specific features identified in these narratives are already extant. Individual elements of agile manufacturing have been implemented in individual enterprises, more or less, thoroughly. The visionary dimension of this report is the systematic implementation of all of the elements required and their assimilation as the norm for industrial practice.

No one scenario is a comprehensive expression of all of the features distinctive to the new manufacturing system. The chemical industry scenario highlights environmental and energy concerns. The semiconductor scenario highlights the information service dimension of the new system of manufacturing. The consumer product is an opportunity to depict the operation of a "virtual company", a multi-venture enterprise. The automotive scenario focuses on collaboration and marketing. The features common to all are flexible production technologies, organizational flexibility, rapid product development, a knowledgeable, involved, work force, and the integration of prevailing social values into managerial decision making.

Scenario: UltraComm Competing Through A Virtual Company Environment

The UltraComm has achieved in less than ten years what it took the automobile, the telephone, even the computer, fifty years to achieve. The UltraComm is everywhere and it is taken completely for granted by everyone who uses one, as people take the electricity grid for granted, or the telephone system. People never wonder how electricity comes to be available at the outlets they use, or how it is that they can call any telephone in the world from any other telephone. They make their calls, and they get through; they plug their appliances into the wall and the electricity is there.

So it is with the UltraComm. Computation, multi-media communication, and an array of constantly expanding information services, from real-time foreign language translation to electronic "newspapers" to access to book, music and film libraries, are instantly and always available. Operating police, fire, and military services without UltraComms is unthinkably primitive. How could firemen effectively fight fires without having the plans of the buildings they have to enter available to them? How could military units function effectively without continuously updated multi-media information on their own, and on the enemy's positions, their equipment, their operations?

Not having an UltraComm installed in the dash of your car, in the control panels of planes, trains, and trucks is almost as unthinkable. How could you travel safely and efficiently without the continuous monitoring and diagnosis of vehicle functioning that UltraComm provides, not to mention the position-locating, mapping, and route-creating services? Not having one on every desk at school, at work, at home means you're just not in the twenty-first century at all. How would you get information from, transmit it to, and share it with, anyone in the "civilized" world without everyone having UltraComms? But how did it come to be that way?

Disassemble a Medieval water mill, a nineteenth century steam engine, a late-twentieth century electronic computer, and you can get a pretty fair idea of the technological capabilities of the societies that produced those machines. The UltraComm is different. Take one apart. You will learn a great deal about the state of production technology in 2006 and you will be impressed by its sophistication. But if you conclude that the UltraComm is an evolutionary product, an extremely compact combination of computer, cellular telephone, fax machine, and modem, you would be wrong. The UltraComm is revolutionary, but what is revolutionary about it is not the satellite access, allowing world-wide communication and access to global information networks. What is revolutionary is the process of its manufacture, which does not leave its traces in the parts of the machine.

THE VIRTUAL COMPANY

From the perspective of 2006 it is clear that UltraComms were the first product of the Factory America Network. When the UltraComm was introduced, in 1996, no one company could have produced it, yet the underlying idea was obvious and compelling. People were swamped by ever-rising levels of potentially useful information that was very difficult to access, and by more and more electronic devices that they needed to learn to use, interconnect, and maintain. The UltraComm promised to unite the devices and the information access. To be sure, no company possessed the hardware, software, and information services expertise to accomplish that unification. Nor were any of the companies that could contribute to creating the UltraComm prepared to accept, alone, the financial risk of creating a new company with the comprehensive capability of designing, manufacturing, marketing, and supporting UltraComms.

The answer in the early 1990s might have been a consortium, and consortia have had their share of successes. By the mid-1990s, however, the adoption of common information exchange standards by thousands of manufacturing firms made an alternative arrangement possible: the creation of a "virtual company". UltraComm, Inc. is an electronic entity linking thousands of employees at over sixty companies all over America. There is no single facility to which all UltraComm employees come to do their work. Indeed, there are very few UltraComm employees at all.

There are a number of final assembly facilities distributed across the country and these buildings bear the UltraComm logo. Suppliers ship UltraComm subassemblies to these plants from which completed units are delivered directly to customers. An electronic record is kept of the custom features of each unit ordered and embedded in a "smartchip" on the UltraComm itself. Because of the precision manufacturing made possible by common data exchange standards, and a shared design and production information environment open to all companies involved in UltraComm, these subassemblies are almost all snap together units. Even in 1996, therefore, robot assemblers were the most cost-efficient technology to use. This followed the example of the highly successful Motorola pager of the early 1990s. As a result, UltraComm employment at these assembly facilities is very low.

Also like the Motorola pager, UltraComms are manufactured to order, requiring minimal stocking of subassemblies. In spite of their much greater complexity and greater customizability, the superior flexibility of modern "intelligent" manufacturing technologies has allowed UltraComm, Inc. to honor its pledge of shipping within twenty-four hours of an order's receipt, and generally well under that. Orders are entered from anywhere, by logging onto the corporate network, UltraNet, accessible directly or through the Factory American Network of which it is a part. From a home/office computer or terminal, using an expert systems-based program that is a direct descendant of Digital Equipment Corporation's XCON system for ordering VAX minicomputers, the order entry program steps customers through the options that are available and their cost. When the completed order is charged to a credit account, the program automatically transmits the relevant information to inventory and to the production control computer.

Shipping is expedited by requiring no special packaging. UltraComms are designed with sufficient ruggedness that they can be shipped in containers made of recycled material recovered from manufacture of the UltraComm cases themselves, with a corrugated cushioning sleeve insert. In addition to eliminating packaging, this design choice reflects UltraComm, Inc.'s sensitivity to environmental issues and to the efficient use of energy and materials. It also reflects the special interest of the Department of Defense in UltraComms.

The military applications are obvious, so it is not surprising that DoD was one of the original partners funding UltraComm, Inc. and contributing technical expertise to its design. DoD is a valued customer because of the volume of its orders, but UltraComms have always been designed to require no special modification to meet DoD requirements. The observance of high commercial quality standards and provision for DoD customization needs in the basic UltraComm design, make UltraComms a single product with an extraordinarily wide range of applications. As every unit is made to order, there is no extra cost for defense versions of UltraComms, while the information services provided to military units are, of course, largely unique to the Department of Defense. An additional benefit of their modular design is that UltraComms are regularly reconfigured for varying military mission requirements by exchanging subassemblies instead of purchasing new units.

In addition to the final assembly plants distributed across the country, and today all over the world, there is also a small headquarters building flying the UltraComm flag. A permanent managerial staff was created by the founders of UltraComm, Inc. Over time, it has been adjusted in size and composition to reflect the volume and nature of the products and services provided by the corporation, as well as the interests of the constellation of

In its Boynton Beach, Florida, manufacturing plant, Motorola has installed a robot assembly line for its "Bravo" model cellular pager. With only eighteen months planning, Motorola engineers were able to complete "Operation Bandit", so called because of the intensive borrowing of ideas from other manufacturers who have experimented with robot assembly operations.

The key to accomplishing this was the redesign of the original pager to accommodate robot assembly, checking, and adjustment, and the installation of cost-accounting measures that redefine overhead as a function of product cycle times.

This is a true "lights out" minifacility, producing half of the total output of Bravo pagers, each of which is different from the others, and building each one without human intervention in eighty minutes from receipt of the order. Approximately twelve human workers monitor the facility's operations and maintain the parts inventory. Twenty-seven computer-controlled robot assemblers do everything else, receiving their instructions from mainframe computers at Motorola headquarters in Schaumburg, Illinois, into which sales staff are tied through their Macintoshs.

companies providing those products and services. The managerial staff monitors and coordinates production operations, new product and services development, sales, and customer relations activities. It also maintains the centralized financial records of the corporation in order to reimburse member companies for their expenses and disburse profits in accordance with agreed upon value-added contributions. Its most valuable function, however, is encouraging initiative and creativity in its distributed work force. It does this by determining education needed by employees for production system improvements, and for R&D.

What made UltraComm possible was the ability to quickly create a hierarchy of project teams whose members were drawn from companies with the expertise necessary to design, manufacture, and market UltraComm. The founders turned to the Factory America Network, or more accurately to FANit, the name of the Factory America Network for identifying project integration teams (thus the "it" suffix).

FAN itself was just taking shape in 1995 as a national industrial data base. Modelled loosely after academic data bases of the late 1980s, subscribers to FAN could quickly learn where R&D work of interest to them was being done, by whom, and with what results to date. Like an ultimate Yellow Pages Directory, FAN provided elaborately cross-indexed information about manufacturing capabilities, materials handling facilities, software development, engineering services of every kind, hardware and software product availability (together with price and performance data), marketing, and customer service expertise. FAN was the first electronic "map" of industrial America. With it, you knew where you were and how best to get where you wanted to go; without it, you were "flying blind", as industrialists did before FAN.

Using FANit as an organizing tool, the group of academics, manufacturing executives, and visionary information scientists who first imagined UltraComm identified an initial project team. This pilot team was made up of people with the knowledge necessary to define what it would take to create UltraComm and to make it a commercial success. The members of the pilot team, as all the subsequent contributors to UltraComm, remained at their companies and on their own company's payroll. With few exceptions, they interacted by computer and by teleconferencing: after all, UltraComms didn't exist yet! At this point, their time was an investment their employers (or in some cases they personally) were making in the UltraComm concept, with the prospect of a substantial return on this investment.

The members of the pilot team laid down the parameters for the design of the first UltraComm, almost amusingly primitive by comparison with today's models, but conceptually as bold as the first, truly primitive, microcomputers back in 1977. What was most innovative about the design was that it was not an engineering exercise, nor did it stop at factoring manufacturability, service, and repair into the engineering design. The most innovative thing about UltraComm, at the time, was that its pilot team's membership represented every aspect of the projected product's total life cycle. Consideration of what the UltraComm would be used for, how it would be used, how it would interact with its user, how it would be sold, repaired, replaced, upgraded, become obsolete, be disposed of, were all added to the list of design parameters.

Using their initial design as a guide, and again turning to FANit, the pilot team created a network of project teams whose members together possessed the ability to make UltraComm real. It would not be enough simply to synthesize the design requirements into a functional product. From the day of its release, UltraComm had to be supported by an array of built-in software, and network—available information and customer services, that would make the UltraComm feel indispensable to the buyer from its first use.

UltraComm, Inc. came into existence with the approval of this design plan by the employers of the project team network and their formulation of a joint financial plan to produce the first generation UltraComm. The cumulative experience of the many manufacturing consortia and collaborations formed during the 1980s and early 1990s had led to substantial revision of U.S. anti-trust legislation. Congress eventually acknowledged that U.S. anti-trust legislation had become increasingly irrelevant in a global competitive environment and adjusted it to protect American business and consumer interests given the competitive realities of the 1990s. That meant one less worry in getting UltraComm started. But if the accounting practices, cost management philosophy, legal complications, and lack of strategic planning characteristic of American manufacturing corporations in the 1980s hadn't changed, that would have been enough to stop the new venture right there.

For convenience, then, and for consumer product identification and confidence, UltraComms all bear a single logo. In truth, however, the company producing and supporting UltraComms doesn't exist as a physical entity. It is an electronic mosaic of a fluctuating number of participating companies, generally numbering about sixty, not counting the suppliers with whom

they separately contract. These companies share in the profits in accordance with the value of their contributions, as agreed upon in the financial plan. The assignment of profits is regularly updated as the balance of the value added by each company shifts among suppliers of hardware and software upgrades, information and customer support services.

The revolutionary dimension of the UltraComm was thus the information and organizational infrastructure that made its creation possible. This included:

- The availability of FAN and the use of FANit.
- The capability of forming multi-functional, cross-enterprise project teams at the operational level of a firm's managerial hierarchy.

  This capability was in turn made possible by a wider distribution of managerial authority than was customary until the mid-1990s. Management had to accept trusting and valuing the knowledge and initiative of the operational work force.
- The existence of integrated manufacturing enterprises, in which all facets of the enterprise are considered in operational, as well as in strategic planning, activities.
- The existence of common information exchange standards within companies and between companies.

  Within companies, a uniform information environment makes it possible to integrate engineering, manufacturing, sales, ordering, inventory, design, and R&D operations.

  Between companies, uniformity permits integrating operations across company boundaries with complementary operations of suppliers, customers, and partners in collaborative ventures.
- Experience with modular enterprise structures which, given a shared information capability, makes practical the formation of "virtual" companies out of appropriate units of cooperating whole companies.
- A management philosophy adapted to long-term manufacturing investment and long life-time product development, including participation in multiple enterprise ventures.
- A new "social contract" for employment, in which employees assigned to project teams can identify completely with a project while remaining loyal to their "home" company. Employees can thus enjoy the stability of working for one company and the professional challenge of contributing creatively to a range of projects in a variety of "virtual" companies.

These infrastructure and organizational developments do not exhaust the revolutionary character of the process by which UltraComms have been manufactured. The ability to create and develop a complex new product, concurrently with its manufacturing process, by geographically, institutionally, and functionally distributed project teams was a bold extension of the system pioneered by Boeing for its 777 model aircraft. The modularity of the UltraComm's construction is a reflection of the distributed nature of its manufacture. But it is also a reflection of what was in 1995 an unprecedented incorporation into product design of its projected use.

The genius of the UltraComm lies in its almost endless configurability. There is an UltraComm model for any application that requires a combination of communication

The Boeing 777 looks like an evolutionary product, but its design incorporates revolutionary managerial innovations. The 777, a two engine, wide-body, plane capable of flying hundreds of passengers across long ocean routes, is being designed by over 200 design/build teams. The members of each of these teams cut across all Boeing functions and include representatives of suppliers and customers. Manufacturing personnel are prominently represented, to ensure that no part is designed without taking into account its manufacturability, and to bring manufacturing expertise into the design process.

The teams are organized around parts of the aircraft, rather than function, and they are dispersed at eleven different locations in Renton, Washington. Team members are linked by 2000 computer terminals running the same three-dimensional CATIA design software. Nevertheless, where teams can be grouped in one workplace, they are, in effect creating "little companies" whose product is the part that team is responsible for.

Boeing is aiming at a "paperless" design. All of the data, "drawings", and models necessary for manufacturing the plane will be digital. There should be little or no need for hand drawings, large-scale mockups, or master physical models. Boeing will deliver simulators to customers before the 777 begins its test flights, so they can start flight crew training early. Similarly, flight and maintenance manuals will be delivered well before the first aircraft are delivered, again to give airlines a headstart.

The 777 workforce is already over 5000 and will increase to over 7000. Boeing management, as part of its Continuous Quality Improvement program, is attempting to involve the entire workforce in making the 777 as good a plane as possible. Once each quarter, all 5000+ workers have off-site meetings at which they are briefed on the status of the plane's design and the decisions that the design/build committees have made. Everyone is actively encouraged to make constructive suggestions.

[Source: Aviation Week and Space Technology, 6/3/91]

capabilities, access to remote information, and computing power. Is it any wonder that UltraComms are ubiquitous? Their indispensability derives from the value attached to the information access they provide together with the utter simplicity of their use.

The simplicity of use was designed in from the beginning, with the concurrent development of user software and hardware. In this way, from the very first unit shipped, the UltraComm was delivered with software that told the buyer how to use it as each function was selected. Voice synthesis technology has come a long way since 1996. Even in 1996, however, vocalized instruction was a vast improvement over the elaborate text-based instruction that was then considered state-of-the-art. In addition, built-in self-monitoring and diagnostic software actively advised the UltraComm user on how the functions selected could be performed better, as well as on maintenance or service required.

Every UltraComm is individually addressable—each one is an enhanced telephone after all—and its particular set of features is recorded on a ''smartchip'' installed in the unit. Owners can, therefore, upload their usage patterns at any time to UltraNet and learn of any software or hardware upgrades or improvements appropriate to their needs. New software can be downloaded at once; new hardware is generally a matter of snapping one subassembly out and snapping a new one in. In either case, the unit's ''smartchip'' is updated with the changes made so that service and status information is always current.

Product failures are, needless to say, rare occurrences. UltraComm, Inc. pioneered the transition from quality as mere reliability to quality as customer gratification. The quality control requirements on suppliers that this imposed could only be met by the intensive use of computer modeling and simulation, and by software prototyping of both product and manufacturing process throughout development. When failures do occur, the customer receives priority replacement with a new unit of the same configuration. The failed unit is recovered for study and the lessons learned are disseminated to appropriate parties. Every product failure is entered into the cumulative UltraComm performance data base (to which consumers have access) along with the action taken in response to it. Old units are always returnable for remanufacture at a substantial saving over the purchase price of a new unit.

The end result is that UltraComms never become obsolete. They are as capable at any given time as their owners want, and can afford, them to be. If foreign language translation requirements, for example, are modest, an owner can log on to UltraNet and pay for them on-line using the system computers. If translation needs are intensive, buyers can have the latest neural net chips, trained to the languages of their choice, installed inside their unit. At the moment, only two languages, and only one of those oriental, can be installed in hand-held UltraComms. More than that and you need to use a console unit with access to more computing power. But improvement is promised in the near future!

Generic Features of Agile Manufacturing in the UltraComm Scenario:

1. The creation of a dynamic multiple enterprise venture as the quickest and most efficient means of synthesizing a response to a market opportunity.

   The legal barriers to the formation of cooperative ventures have been removed.

2. Uniform information standards, and a broadband communication system, have been put in place to make the formation of a ''virtual'' company, with distributed design, engineering, and manufacturing, a practical option.

   Factory America Network and subsidiary services are an available resource.

   The cooperative structure of the partnership is dynamic in that the membership in the partnership changes fluidly in response to evolving product, process, and service requirements.

3. Indefinite product longevity.

   The product is continually improved after purchase, through reconfigurability and upgradeability to match changing user requirements.

   Longevity is a consequence of modular design, but more generally of a design process that factors longevity, reconfiguration, and upgrades into an evolutionary design framework. Discontinuous product families, entailing replacement of obsolete products, gives way to extended product families that are mutually compatible over time.

4. Long term customer-manufacturer relationships, as well as manufacturing partners relationships, are a corollary of product longevity.

5. The distributed work force reflects a new ''social contract'' between employers and employees.

   Management authorizes initiative at the operational level on the basis of mutual trust: commitment to making cooperative ventures work is consistent with loyalty to the long-term employer.

6. The implementation of accounting and managerial measures appropriate to establishing the value to the company as a whole of committing resources on a long term basis to multiple enterprise ventures.

Scenario: U.S. Chemicals Simultaneous Cooperation and Competition

Mr. Mayor, members of the Boston City Council, Ladies, and Gentlemen. On behalf of U.S. Chemicals Corporation I want to thank you for arranging this reception and for inviting me to address this audience, gathered to share what is, at least in a small way, a momentous occasion.

For the first time in half a century, a chemical plant has been built within a major U.S. city's limits with the enthusiastic approval of just about everyone. As a matter of fact, this is the first of three inner city plants that U.S. Chemicals will be opening on the East Coast this year. Two more will be completed in the Pacific northwest next year and—can you believe this?—we will be opening a plant three years from now, in 2009, in Los Angeles. We learned of the final approval of that facility by the California Department of Environmental Protection just as I was leaving corporate headquarters to address this opening ceremony here in Boston.

What a turnaround! Fifteen years ago, back around 1990, the chemical industry was *the* industrial "bad boy" in the public's eye. In spite of being one of the few sectors of industry that remained profitable, and even expanded, in those difficult times, it seemed that we could do nothing right as far as public opinion was concerned.

Chemicals manufacture was equated by many with air and water pollution, even though by 1990 all of the large companies *wanted* to achieve zero discharge processing, and were spending large sums of their own money to learn how to do it.

The use of industrial chemicals was similarly equated with toxic, or at best noxious, wastes that polluted the land and inevitably contaminated the groundwater. And California? Well, before the CDEP *really* got serious about emissions regulation, one of our competitors, Dow, found that it had to file 560 forms every year for an *existing* plant's *approved* emissions, and 373 *more* for the emissions from the sources of the materials they used in that plant. It was the last plant they built in California for a long time.

How did things turn around? And why? There are a number of responsible factors and I'd like to review the major ones with you. They are symptomatic of a profound change in the American system of manufacturing and in the relationship of society to industrial technology.

The first factor responsible for the turnaround is actually a cluster of four interrelated developments whose joint impact on chemicals manufacture has been enormous. Those four developments were in the areas of environmental sensitivity, energy efficiency, scale of operations, and computing power. Environmental concern became a driver of change in the chemical industry in the 1970s. Substantial progress was made through the early 1990s in controlling emissions from plants, in recovering toxic byproducts, in transporting, storing, and treating wastes. But this progress was incremental. It accepted the existing way of doing business and ameliorated as much of its negative impact on the environment as was thought possible at the time. What we needed was a We're-Going-to-the-Moon commitment, and we got it with the joint declaration by major chemical producers of achieving zero discharge chemical manufacture as of the year 2000.

The situation was pretty much the same in the area of energy efficiency. After the fuel price rises of the 1970s, the chemical industry aggressively pursued energy reductions. We improved the efficiency of our operations and we sought, and frequently found, alternative reaction paths, requiring much lower energy inputs, to the same end product. Together, these two approaches reduced the chemical industry's energy usage 30 percent between 1975 and 1990, an average of 2 percent each year. At the time, we thought that was pretty good and we expected to do even better in the 1990s. None of us, however, anticipated how much better we would do.

Quite independently of environmental and energy cost reduction concerns, developments in the chemical industry began to favor smaller scale operations. New, "intelligent", process control, sensing, and sampling technologies dramatically increased the flexibility of chemical production equipment. The result was reduced lead times, lower unit costs, and improved quality.

These technologies linked powerful new sensors and analytical tools capable of real-time sample analysis to computers running expert system-based software that monitored and diagnosed the data the sensors collected. With these in place, we could change the mix of materials flowing through the same processing equipment, the rates of flow, and what was done to the materials, far more rapidly than before. We were also able to monitor what was happening to the materials at every stage in their processing, as it happened to them, and to adjust the processes instantly to keep them within specifications.

The impact of these technologies was to make speed to market a major competitive advantage, which drove installation of the new technologies. Those companies that installed them could respond much more quickly to customer orders than those companies that did not. Furthermore, these same technologies permitted companies to match the characteristics of the chemicals they produced more closely to the particular requirements of individual customers at little if any additional cost. And the instantaneous process control the new technologies made possible uncoupled quality from cost. We could make the highest quality product the process was designed to produce at no greater cost than a mediocre quality product. *That* was a competitive advantage.

The "good old days", when we ran the plant, tested the product, sold the good stuff at a premium to demanding customers and the not so good stuff at a discount to off-brand wholesalers, are gone. So is the automatic economic advantage of building large-scale plants dedicated to a single product. If speed to market gives competitive advantage, then smaller-scale plants capable of producing a variety of products interchangeably, capable of "on the fly" reprogramming of their equipment, become attractive.

As we explored the potential of these technologies, we found that the biggest economies came from highly flexible, small- and medium-scale plants, often built right on the customer's site. Having a flexible plant at the customer's site offers many advantages. Transportation is eliminated, for one thing. Quite apart from cost, the real saving there is environmental and safety. If the product shipped is noxious, corrosive, or toxic, rail or truck accidents, then the harm they can cause to people, property, air, and water, are avoided. Shipping was a major factor in the decision to locate the plant we're opening today in Boston. All of its output will be used by customers within a radius of twelve miles of the plant.

A second advantage of on site, or near site, manufacture is the close relationship that develops between vendor and customer. Our engineers can work much more closely with customer engineers to better understand what the customer needs and how to produce just exactly that. In addition, we can also work with the customer on how best to use the products they buy from us and to assist in dealing with residues, byproducts and wastes. By tapping into ChemNet, the chemical industry data base that is part of the Factory America Network, we can discover which companies are using any of these materials as inputs to their own manufacturing processes. Where we find a match, the "waste" suddenly becomes an income-producing raw material. Where we don't, and if we cannot reprocess it, then we verify the state-of-the-art treatment and arrange for that on the customer's behalf.

Toyo Engineering Corporation of Tokyo has introduced a modular design, next-generation, pipeless chemical plant suitable for batch processing. Piping materials through the plant from one piece of processing equipment to another is replaced by moving a single reactor vessel from one modular processing station to another. Installed on a robot transporter programmed to follow a particular path, the reactor vessel is sequentially coupled to the appropriate equipment. The coupling and uncoupling is automatic and unattended.

The advantage of such a system is the extreme flexibility it allows for producing any chemical within the range of the installed processing equipment. There is no need to reconfigure the plant when switching from one product to another. The processing stations are modular and modules can be added or subtracted depending on the range of products anticipated. Instead of reconfiguring the plant when changing products, the robot transporter is reprogrammed to follow a different path and the processing equipment is programmed appropriately. Eliminating pipes also eliminates leaks and reduces the likelihood of accidents. The increased safety of the workplace and of the external environment are additional virtues of Toyo's system which is, however, limited to relatively small volume, high value-added products, at present.

In the area of high value-added chemical manufacture, where the amount of product in each run is small, the new process control technologies allowed us to build pipeless chemical plants of very high flexibility. These plants all contain the same wide variety of generic processing equipment: heaters, mixers, controllers, and so forth. The reactor vessel containing the materials being processed moves automatically, according to a programmed sequence, from one piece of processing equipment to the next. At each stop it automatically connects to the equipment, whose process control computer "reads" the instructions coded into a microchip on the reactor vessel, and does what the program calls for. The vessel then disconnects itself and moves on. Where the economics favor batch chemical production, the energy efficiency gains, workplace safety improvements, and environmental benefits of pipeless plants are substantial additional incentives for using this technology.

These three developments, then—closer control of environmental impact, of energy used in the total production process, and the installation of "intelligent" process control technology—substantially improved the conduct of chemical manufacture. But the fourth development tied all of them together in a way that truly transformed the industry and made today's ceremony possible. This fourth development was the availability of enough computing power to model industrial chemical reactions in real-time. With this kind of computing power, we could study the detailed properties of compounds before we produced them. We could construct simulations of complex reactions and explore how changes in reactants would affect the energy input required and the byproducts produced.

Supercomputers are expensive, even today. Expensive as they are, however, the cost of experimenting with many different reaction paths to the products we needed to arrive at is vastly lower using computer simulations than building pilot plants. With intensive computer modeling of reactions, and the existing experience we had with detailed computer simulations of chemical processes, we were able to eliminate the need for pilot and intermediate scale plants completely. Even laboratory demonstrations became an optional check on the computer output, rather than a proof of concept. Further, the combination of computer modeling and computer-based process control shortened product development time. That reduction in the time to bring a new product to market gave us yet another competitive edge. Equally important, the industry could commit itself to a zero emissions philosophy, and mean it!

The smaller scale of new plants, the close process control we could now exercise, and the computer-based R&D often allowed the identification of cost-effective alternatives to reactions that produced toxic byproducts. Where that was not possible, the smaller scale meant that the volume of undesirable byproducts that needed to be captured and treated in any given location was much more manageable than in a large plant. With zero emissions a practicable ideal to which the industry committed itself, we went one step further.

Our objective now is to make chemical plants environmentally neutral and positively beneficial to the communities in which they are located. We do *not* harm the air, water, or land around us. We *do* provide good jobs and a safe workplace. We support the personal and professional growth of all of our employees because that is a company asset in the long run. We recognize our obligations to the communities in which we operate and we remain open to their particular needs and sensibilities. Your response to this facility is a sign that we are accomplishing the ideal of zero emissions and the objective of positive community benefit.

I've talked at considerable length about the impact of technological developments on transforming the chemical manufacturing process. But there are two other major factors equally responsible for the industry's turnaround. These are people factors, not technical innovations. One of these could be called a new philosophy of management, the other a new attitude toward, and within, the work force.

Flexibilty at the level of the tools of manufacturing, however sophisticated those tools may be, is only potential. It becomes actual if the organization of the manufacturing enterprise is adapted to the flexibility of its production technologies. The competitive benefits of flexibility follow from the synthesis of the matched capabilities of technologies, organization, and work force. As we installed the new technologies that became available in the early 1990s, U.S. Chemicals committed itself to total enterprise integration. We wanted all of our planning to include input from all phases of our operations. We wanted the computers in accounting, in sales, in inventory, in engineering, in purchasing to be able to "talk" to one another effortlessly. We wanted the process control equipment to be accessible to the engineering department. Incredible as it seems to young people today, this seemingly obvious requirement was not the rule as recently as fifteen years ago, and not just in our industry either.

Integration of individual enterprises, we found, was not enough to fully exploit the competitive advantages that the new technologies allowed us to gain. With our new technical capabilities, we needed to interact much more often, much more closely, with other companies. We needed to exchange detailed technical, price, and scheduling data with our suppliers and with our customers. We couldn't do that if our internal computer networks were incompatible with one another, or if we observed a different data standard in our software than they did. Furthermore, as more and more companies turned to ChemNet to learn who was doing what with what materials, competitors turned into potential allies. And ChemNet taught us another lesson. The more information we exchanged with other companies, the more we appreciated the value of information. In addition to adding value by manufacturing chemicals, we discovered that we could sell manufacturing information services. Through ChemNet, we could make more intensive use of our computing resources and our technical knowledge base by providing reaction modeling and process simulation services at a fee. We learned that this brought us more customers, not fewer.

Before identifying any material as waste, we learned to search ChemNet to find who might need some intermediate or by-product that was waste to us, or to one of our customers. It soon became obvious that temporary local consortia among a group of chemical companies could quickly bring certain products to market at a far lower price than any one company could. Consortia could accomplish this by calculating the optimal distribution of materials to processing facilities and to markets. If the raw materials necessary to make a product were located near a company with an existing facility capable of initially processing that material and reducing its bulk, that would lower transportation costs. If, in addition, the residue could be sold locally, that lowered the overall production cost still further.

You can imagine the other options such arrangements could permit. The upshot was that chemical companies in 2006 routinely stand to one another as customers, competitors, suppliers, and partners at one and the same time. Some branches of U.S. Chemicals are today competing with some branches of Dow and Du Pont and Monsanto. Others are engaged in temporary collaborative ventures with them. Some are selling to these "competitors" and some are buying from them. These interactions, which are today fundamental to the competitiveness of the industry, and to our environmental and energy achievements, required major adjustments inside and outside chemical corporations.

Inside, management needed to distribute authority more widely, to encourage initiative in searching for collaborative marketing opportunities. In turn, that required encouraging the formation of project teams drawn from different branches of the same plant, or from different divisions of the corporation located anywhere in the world, and even from different companies. Imagine that happening back in the 1980s, when ordering a new copying machine could take months for approval in large corporations!

Outside the corporation, legal, political, and social adjustments were necessary to make the formation of temporary consortia among traditional competitors easy and rapid to accomplish. Wait six months, let alone three years or more, for Justice Department approval, and the market is gone, almost certainly to a foreign competitor. In retrospect, then, the creation of consortium models and pre-approved collaboration mechanisms, though on the face of it far removed from chemical manufacturing technology, were key elements in moving the industry away from its old image.

> Monsanto Corporation's thirty-nine year old Pensacola, Florida, chemicals complex is running at its highest safety and productivity levels ever, five years into a worker self-management program. Introduced after the plant operated at a loss for the first time, workers now make hiring and purchasing decisions, assign jobs, and determine the production schedule. There are no foremen; first-line supervisors coordinate ten to twelve member work teams and are responsible for their training. On their own initiative, workers alter the mix of chemicals producing nylon, shut down production lines for safety or quality reasons, and recently pulled the plant out of the utility grid when thunderstorms threatened, switching over to in-house power just before power lines went dead. The managerial hierarchy has already been reduced from seven layers to four, and one more layer is slated for elimination.
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> [Source: NY Times, 6/25/91]

Last, but certainly not least, the turnaround in the public's perception of the industry was made possible by a new attitude towards the work force. Competitiveness has increasingly come to be dependent on having knowledgeable workers at every position in the company. Every worker is encouraged to learn the total manufacturing system and to be thinking all the time of ways to improve it and exploit it. This has meant far more training and formal education at company expense than even the most progressive corporations engaged in in the twentieth century. We justify that today by looking at training and education expenses as long-term investments, not short-term costs. It's the same kind of attitude change that converted "wastes" into resources.

The new competitive environment has made it more evident than ever before that the central asset of any chemical company is its work force. Flexibility, spontaneity, rapidity of response, creative reconfiguration of equipment and processes, actively seeking out and creatively interpreting relevant new information: that's the lifeblood of the new chemical industry. To keep that

lifeblood flowing takes people *using* technologies. It can't be done by technologies alone. It also takes trust, between management and workers, among workers, and between companies.

Historical adversarial relationships are an insupportable competitive burden today. Daily, we as a company probe the limits of trust; and every day we learn how much more open we can be without suffering for it. Without trust, the kinds of relationships I have discussed between competitors, suppliers, and customers could not be formed. The people involved in these relationships need access to technical and business data that is accurate and available on demand. There's less and less that can be justified as proprietary in that kind of environment. What's true between companies is true within companies as well. If workers do not have access to all relevant data, they cannot play the dynamic role they must play for U.S. Chemicals to be a profitable enterprise. If we have to compete against even one rival with a more knowledgeable and more motivated work force than ours, we're at a competitive disadvantage. That's a pretty strong motivation for nurturing a relationship of trust, and for valuing workers as highly as they deserve to be valued.

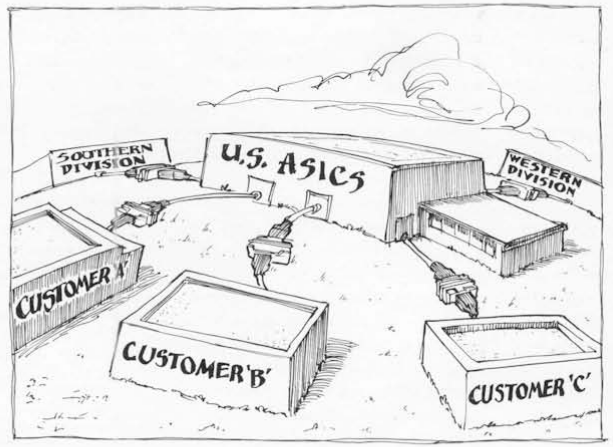
Which brings us to Boston on this fine day in 2006: a fine day for U.S. Chemicals Corporation, a fine day for our personnel who begin work in this new plant, and we hope a very fine day for Boston.

Generic Agile Manufacturing Features in the U.S. Chemicals Scenario:

1. The synergistic consequences of integrating separate coexisting elements: almost all of the pieces of the chemical industry envisioned here exist today, in 1991, but they are not routine and they are not yet systematically interrelated.
2. The assimilation by corporate management of social values as policy drivers, especially environmental values, but also workplace safety, energy efficiency, and the social impact of manufacturing operations.
3. Redefinition of "competition", now compatible with routine close cooperation among marketplace competitors at the generic technology level, and sometimes at the product level.
4. Technical knowledge bases are used to competitive advantage.
5. Products incorporate scientific knowledge of materials and manufacturing processes.
6. Intensive use of computing power allows the properties of new products and and the behaviors of new manufacturing processes to be predicted in advance.
7. The work force is treated as an asset, appropriately trained and educated, and authorized to exercise spontaneous initiative in using its knowledge in the company's interest.
8. Real-time closed loop process monitoring replaces after-the-fact sampling.

Scenario: U.S. ASICS Competitive Advantage From An Open Information Environment

With the gift of hindsight, one can pinpoint just where the semiconductor industry fell off Moore's Curve, but at the time it wasn't at all obvious. Semiconductor industry pioneer Gordon Moore had predicted back in the early 1970s that the cost of semiconductor devices would halve, and their speed double, every three years. Incredibly, this rate of improvement was sustained for over twenty-five years, right through the introduction in 1996 of 256 megabit DRAMS and the quarter-micron fabrication technology that made them possible. Naturally, the Japanese were the first to accomplish this, allowing them to continue the near-total dominance of the chip market that they had enjoyed since the mid-1980s.



Everybody knew that some day that rate of increase would have to slow down, but the Japanese decided they could commercialize .15 micron technology and squeeze a billion bits onto a single chip. They did, but the cost per bit of this technology proved to be so much higher than the cost per bit of the 256 megabit DRAMS, that the gigabit chips never went into mass production.

That provided the opening that U.S. industry needed and was positioned to exploit. Through cooperative ventures stimulated by Sematech, the Microelectronics and Computer Consortium (MCC), other consortia inspired by these two, and such breakthrough projects, as the Air Force Microelectronics Manufacturing Science and Technology Program, U.S. computer, components, and peripherals manufacturers had maintained an aggressive competitive posture. True, with the collapse in 1990 of the US Memories initiative, IBM remained the only independent domestic manufacturer of DRAMS. IBM could afford that because it was its own, and only, customer; and because the technology it learned by remaining at the cutting edge of memory chip manufacture transferred to other vital manufacturing operations. DRAMS, however, were not a good measure of competitiveness. They were a product of the mass production manufacturing system. By the early 1990s, U.S. industry was already beginning to identify the outlines of a system of customized manufacturing.

In addition, DRAM fabrication facilities had become prohibitively expensive, exceeding $200 million for a single 1-4 megabit plant and rising to the $1 billion it would cost by the late 1990s to reach the 64-256 megabit range. Individually, DRAMS were very cheap and competition kept unit profits very low. The only way to make money was by producing and selling truly vast quantities of these standard items. What U.S. manufacturers began to focus on was a smaller scale, modularized, flexible mode of production with which they could offer customers rapid delivery of a wide variety of highly customizable semi-conductor products. By refusing to be drawn into DRAM competition, U.S. companies were able to support a broader base of R&D than would otherwise have been the case.

This strategy proved to be wise as the semiconductor industry shifted from the Moore Curve to a new, as yet unnamed, curve just before the turn of the century. The new curve expresses the onset of maturation of a different "family" of technologies than had driven the industry's growth from the 1960s to the mid-1990s.

By 2000, silicon chip-based, sequential processing, computers with magnetic storage devices were rapidly giving way to computers with radical new processing architectures, using other kinds of chip materials, integrated into optoelectronic circuits. These incorporated optical storage devices of enormous capacity and very rapid access times. Leading edge supercomputers began

to employ superconducting materials in their circuitry and achieved performance improvements 1000 times greater than the best machines using the older technologies. U.S.-led software breakthroughs released the power of hybrid computer architectures synthesizing massively parallel, neural net, and sequential processing structures. New applications for semiconductors emerged in consumer electronics, "intelligent" industrial process control equipment, education, and entertainment.

The upshot of this extraordinary surge of innovation was, if anything, an even faster rate of technological advance along the new curve than the industry had experienced on the steepest portion of the Moore Curve. U.S. ASICS, Incorporated was founded in this atmosphere of rapid innovation, technological and entrepreneurial dynamism, high stakes uncertainty: in short, in an atmosphere particularly well-suited to American strengths. The kind of creativity and boldness manifested thirty years earlier in the "Silicon Valley" syndrome, now promised to establish an entirely new foundation for the computer industry. The prospect was not just for improved individual technologies, but for a different system of computing, requiring new approaches to the design, manufacture, and marketing of hardware and software.

The founders of U.S. ASICS saw in this dynamism an opportunity for a new kind of semiconductor manufacturing company. By the late 1990s, almost every manufactured product contained "smart" chips that made possible the kinds of performance and diagnostic features consumers had come to expect. These chips were, in fact ASICs, Application Specific Integrated Circuits. ASICs were the "heart" of specialized-function, monitor, control, and user interface devices in every kind of vehicle, in audio, video and communications products, in credit cards, toys and games, in all commercial and industrial equipment. ASICs were becoming ubiquitous, but unlike DRAMS, all of which were identical, ASIC chips had to be custom designed for their particular application.

U.S. ASICS, Inc. management wanted its own manufacturing facilities, but these facilities were designed to exploit fully the latest modular and scalable chip production machinery. Modularity permitted cost effective production of small chip lots, while scalability allowed making as many copies as needed of chip designs that turned out to be "best sellers". The founders of U.S. ASICS recognized, however, that the real value of ASICs manufacture resided in the information embodied in the chip, not in the physical chip itself, paradoxical though that sounded at first hearing. It was the chip design that the customer was primarily concerned about. A company that could make itself indispensable at the ASIC design level *and* possessed manufacturing facilities, would be perfectly positioned in the new marketplace. U.S. ASICS was thus configured to offer its customers a comprehensive set of design services, including the optional "service" of having U.S. ASICS manufacture any ASIC chip design, in any lot size, from one wafer's worth to millions.

To make itself indispensable, U.S. ASICS management established as the trademark of their business practice an open ASIC information environment. Utilizing the Factory America Network (FAN) as a "backbone", they created ASICNet as a commercial service entered through FAN. Customers could log on to FAN, select ASICNet and call up on their own computers a comprehensive and continuously updated ASIC library. Along with price and performance characteristics of all past and current U.S. ASICS products, the library included: generic ASIC chip design information, ASIC device simulations, processing statistics at all U.S. ASICS production facilities, worldwide U.S. ASICS production scheduling information, even individual shop status information.

> All of the pieces are coming together for the formation of a national network of information sources to which personal computer users will have constant, inexpensive, and easy access. The innovative supercomputer manufacturer Thinking Machines Corporation has joined with Apple Computer, Dow Jones, and KPMG Peat Marwick to create the software format for a national computerized library, called Wide Area Information Servers (WAIS). To encourage development, Thinking Machines has put the software in the public domain.
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> WAIS utilizes Internet, a government-sponsored network of 2600 public and private computer networks, for delivering its information, which can be in the form of text, sound, pictures, or video. Apple computer users, through WAIS, can use Thinking Machines computers and network servers to explore the scores of information sources so far linked together, including university libraries, government agencies and federal document libraries, and corporate information services. The Library of Congress, Apple, Next Inc., Sun Microsystems, Dow Jones, and Mead Data Central all support the WAIS information retrieval standard, which is based on a format developed for computerizing library card catalogs.
>
> The format is context sensitive; it can make inferences about the specific information the user is seeking. With the power of supercomputers at its disposal, the network servers can search through vast quantities of data quickly and organize relevant selections for delivery to the user. The government's projected development of NREN, a National Research and Education Network, will, if funded, place access to high-speed computerized information services in schools and communities across America.
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> [Source: NY Times, 7/3/91]

Customers had open access to this database. U.S. ASICS maintained as exhaustive a cumulative data base as possible on individual ASIC chip designs, their production histories, and their performance in products. This design library was available for copying, at a fee, to anyone, anywhere in the world, who logged on to ASICNet using standard chip-CAD software linked to appropriate chip production machinery. The library covered all of U.S. ASICS' designs, all designs in the public domain, and all designs that U.S. ASICS' customers did not withhold on proprietary grounds. The result has been that ASICNet is as profitable an operation to U.S. ASICS as the Sabre airline reservation system was for American Airlines.

Superficially, U.S. ASICS' most valuable asset when it opened for business was its production facilities. In truth, it was its ASIC software design tools. It offered these to customers on terms as flexible as the processing technologies that produced ASIC chips. Customers could lease the proprietary U.S. ASICS software and have their own engineers design the chips they required. If necessary, U.S. ASICS personnel would train the customer's engineers in the use of these tools. The customer could then produce the chips themselves, or have someone manufacture the chips for them, one choice of manufacturer being U.S. ASICS, of course.

Alternatively, a customer could have U.S. ASICS engineers design the chip according to specifications provided by the customer's engineers and, again, arrange for manufacture as they saw fit. The crucial fact is that customers enjoy a competitive advantage because of the reduction of product cycle time gained from their relationship with U.S. ASICS.

Customers capable of designing their own chips, but lacking production facilities, could transmit their design programs directly to U.S. ASICS production machinery, using the highly automated U.S. ASICS manufacturing facility as if it were their own. With the establishment of industry-wide data exchange standards, and with the installation of broadband telecommunication channels, all of these information transactions, including the programming of the production equipment, could take place remotely. Only information needed to move; people stayed put.

At every stage in the chip development process, but preferably early on, before the design was fully specified, U.S. ASICS offered value-adding services to their customers. Contrary to older thinking, they made their software for conceptualizing and designing chips as *easy* to use as possible. In addition, U.S. ASICS provides, on request and at no extra charge, dedicated workstations with proprietary software for easily utilizing U.S. ASICS chip-design programs. Management's intuition that this would attract more customers, rather than create more do-it-yourselfers, has been proven correct.

Customers prefer to deal with U.S. ASICS because they can get involved with U.S. ASICS engineers in working out the chip design and then in generating the mask-sets for producing their custom chips. Having gone this far with them, it is the rare customer who will not also have U.S. ASICS produce the chip from the completed mask-set. And having done business with U.S. ASICS once, satisfactorily, the probability of repeat business has proven to be very high. It simply makes no sense at all to start over again with a different manufacturer, if only because of the loss of priority access to the ASIC data base, including their own products, that U.S. ASICS maintains.

Because of the capability of transferring all of the information the company deals in by fiber optic telephone line or satellite up-link, it was easy for U.S. ASICS to decide to disperse its operations worldwide. Design facilities are, quite literally, only a datacall away from production facilities.

In retrospect, it was insightful of the founders of U.S. ASICS to insist on locating both design and production facilities in developing, and not only in developed, countries. U.S. ASICS management adopted an aggressive policy towards developing-nation location of its facilities, assisting in obtaining World Bank financing, helping to arrange production contracts, and scheduling its own production to give new facilities a start-up order book. By 2000, access to information technologies was *the* sign of modernity. DRAM manufacture was very expensive to get into. ASICs were essential components of virtually any world-class product, however cheap, but hiring firms located in developed nations to design and manufacture ASICs for such products was prohibitively expensive. U.S. ASICS provided a solution, and yet another profitable service.

Engineers in developing nations could work with the local U.S. ASICS personnel on chip design and then have the chips produced in U.S. ASICS manufacturing facilities located in their nation. Because these facilities were modular in design and scalable to the volume of chip production that local industry required, they were more easily affordable. Because of their flexibility, and because of the very nature of ASICs, production equipment did not become obsolete when chip designs changed, as DRAM equipment did. Initially, a single ASIC facility in one developing nation served surrounding nations as well, further offsetting the cost of creating an ASIC industry.

The rapid global spread of U.S. ASICS design and manufacturing centers was reinforced by the company's policy

of hiring and promoting nationals to the highest positions in each facility. American multi-culturalism, and the willingness of U.S. transnational corporations to reward demonstrated competence by any of their personnel, regardless of nationality, have turned out to be major virtues in the global marketplace. Foreign nationals prefer U.S. ASICS as an employer because of the reputation of American companies for cultural openness, receptivity to local input, and maintenance of the high American standards for workplace safety and environmental impact of semiconductor manufacturing operations.

> Retail sales overall were flat last year, but for 100 large retailers and manufacturers using a revolutionary inventory control system, sales were up fifteen percent. The system is called Quick Response and it uses the familiar bar code tickets on sales items and bar code scanners tied to an in—store computer. What is revolutionary about Quick Response is that it ties the retail store and manufacturer computers into a common network with uniform data exchange standards. As items are sold, not only is the retailer's inventory updated, so is the manufacturer's product database. Production and delivery schedules can be automatically updated to maintain agreed upon stocks of models, sizes, and colors much more rapidly than in the past.
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> With the ability of manufacturers to monitor sales in real time, retailers need not carry inventory ordered twelve to eighteen months ahead based on guesswork as to what would be selling at the time of delivery. The key is shared data and a relationship of trust, confidence that neither party will abuse the information they learn about the other.
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> [Source: Phil. Inq. 8/7/91]

In the early 1990s, many semiconductor industry "experts" proclaimed the demise of the large, high volume, clean rooms that were driving the expense of semiconductor manufacturing facilities beyond reach even of the largest companies. As the size of chip features shrank, the control of dirt and of dust particles of ever smaller size became necessary. This became more and more expensive to do in the large spaces required by high capacity production lines. The experts were partly right, but they were wrong in predicting that large chip fabrication facilities would go the way of the dinosaur, replaced by small "micro-fab" facilities. The objectives of production flexibility, rapid setup and changeover, and the ability to sequentially process wafers of semiconductor materials for different chip designs, have turned out to be most cost-effectively realizable in medium and large facilities.

To be sure, these facilities are modular in design and scalable, but unit costs do go down as the scale goes up. Each module consists of a set of flexible cluster tools, each set capable of performing all of the processing steps required in fabricating ASICs. There are no production "lines" at all, really, only production "loops". All of the tools in these clusters are "intelligent", that is, they are programmable and contain monitoring and testing sensors with diagnostic software built in. Each sensor and each tool is in constant communication with the semiconductor wafer that is being processed and with the production system computer.

Following the practices pioneered in the Air Force MMST program, wafers are moved inside small cassettes from tool to tool within a tool cluster, and from cluster to cluster within a production module. Inside these cassettes, occupying a volume not much larger than themselves, the wafers are exposed to an ultra-clean environment. Each cassette contains a chip encoded with the processes to be carried out on the wafer inside it. The sensors on each tool read these instructions—there is no contact with the wafer in doing so—the wafer is removed from its cassette, and the appropriate operation is performed. The tool sensors then test the wafer, return it to its cassette, and enter the results on the chip mounted on the cassette.

The actual tool operations are carried out inside ultra-clean chambers within the tool clusters. Again, only small volumes of air need to be maintained at this level of cleanliness, not the entire production facility. The central system computer remotely monitors each cassette's "smart" chip. If a wafer fails a test, it is immediately rerouted to a repair or reprogramming cluster. If it passes, it moves on. This architecture entails that, for any given wafer, some tools are inactive, because some processes do not need to be performed it. Nevertheless, the openness to expansion and easy modification of the cluster approach, and its overall flexibility, more than make up for the advantages in long production runs of the dedicated tool, closed architecture, of 1980s chip production technology.

U.S. ASICS' success is due largely to its having maintained a steady focus on its goal: achieving competitive advantage in its markets. The measure of the suitability of the technologies it employs, of its customer philosophy, and corporate organization, is the competitive advantage these give. The modular, scalable, decentralized architecture of its production facilities is echoed in the decentralized, modular, scalable architecture of its work force organization.

U.S. ASICS facilities all over the world consist of a basic chip design service "module" and, where appropriate, a basic production facility. Both can be scaled up easily if business volume justifies it, and scaled down as well, though less easily. So far, global business volume has remained high enough that every production facility is kept in operation, though not all are fully employed producing for the market they were designed to serve. Thanks to global broadband telecommunication channels, any facility can be programmed virtually instantaneously to produce chips for any customer. Transportation costs are a modest burden if an underutilized facility in a remote location is used to produce chips for a distant customer, but the overall impact is positive if orders can be filled more promptly.

There are two further benefits of the U.S. ASICS modular and scalable production architecture, and one crucial condition of the corporation's success. From environmental impact and energy efficiency perspectives, this style of production is highly advantageous. Reducing by orders of magnitude the volume of air that needs to be ultra-clean is all by itself an immense energy saving. Reducing large scale production lines to local loops makes the management of toxic and corrosive materials used in chip production operations much more effective.

All the technology notwithstanding, the determining condition of U.S. ASICS' success is its work force. U.S. ASICS is an information services provider, in this case, a provider of comprehensive information bearing on ASIC chip design and production. The company stands or falls on the quality, timeliness, and customer-specific appropriateness of the information it provides. The rationale for the investment in the production technology was to achieve much more rapid product cycle times, delivering customized ASICs faster than competitors could.

The founders of U.S. ASICS recognized that only a knowledgeable work force capable of fully utilizing the technology could realize this goal. They responded along two lines.

First of all, the overwhelming majority of U.S. ASICS employees are physical scientists or engineers by original degree training. Those production workers who are not engineers must have at least two years of technical vocational training at the college level, or its occupational experience equivalent. All U.S. ASICS design and production facility staffs are extensively cross-trained during the first three years of employment and typically are organized into teams, including production workers, in dealing with a customer. Just as the facilities are decentralized and distributed around the world, so too is managerial authority. Upper management's primary function is to identify and/or approve new projects, coordinate operations, monitor performance, maintain the system infrastructure, and motivate the personnel.

Secondly, echoing the constant updating of ASICNet to maintain its value as an income-generating information service, U.S. ASICS invests extensively in constant training and education programs for all of its employees. Every employee finds constant challenges to exercise initiative and creativity and an open opportunity for personal and professional development along a number of lines: technical, financial, managerial, marketing. The result has been a very positive change in the perception of semiconductor manufacturing as a career choice, and an influx into the industry of a growing percentage of bright young people in the developed, as well as in the developing, societies.

Generic Agile Manufacturing Features in the U.S. Asics Scenario:

1. The value added by the manufacturer is explicitly measured by the ability to embed expert knowledge in the manufactured product. Manufactured products become information products. They are valued for the performance-determining information they contain.

   Manufacturing itself becomes a service.

2. Customers and manufacturers work closely and systematically together not just to produce the product the customer has agreed to buy, but to define the specifications of the precise product the customer wants/needs.

   Marketing, design, and manufacturing become mutually interdependent phases of a single operation.

3. Technology is shared to competitive advantage through cooperation, as opposed to the current practice of maintaining competitive advantage by arms length relationships that shelter proprietary technology.

4. The work force skill base is recognized as the agile manufacturing enterprise's most valuable asset and cultivated accordingly.

   Continuous training and education is perceived as an investment, not a cost.

5. Management retains responsibility for oversight and allocation of resources, but authority is widely distributed to encourage initiative.

   Information and communication infrastructures, such as FAN, uniform data exchange standards, and telecommunication channels are taken for granted as adequate.

6. Production machinery is flexible, modular, scalable, keyed to "intelligent" control and sensing devices.

U.S. Motors Scenario: Responds with Agility to Customer Requirements

U.S. Motors was created for one purpose: to raise still higher the rising expectations of car buyers in the 1990s, and to satisfy even those higher expectations domestically. From the start of production, back in 1998, USM Corporation has kept the three Founding Promises that have been the regular refrain of its advertising for eight years now:

- every USM car a custom car;
- every USM car delivered within three days of being ordered;
- total accountability for customer satisfaction over the lifetime of the USM vehicle which, given its ability to be reconfigured, is very long indeed.

These promises could not have been kept by any company, at any price, prior to the mid-1990s. New technologies became available at that time that made an alternative to mass production manufacturing possible. Even with the new technologies, the promises could not have been kept if USM management had structured the corporation along traditional, hierarchical, lines. The corporate structure had to be as flexible as its "smart" general purpose production machinery was if the two were to be integrated into a flexible manufacturing system. The story of the success of U.S. Motors is thus the story of the revolutionary transformation of mass production manufacturing that we take so much for granted today. It is also the story of a company whose management made a commitment to invest in its customers. From the perspective of the car buyer, however, the story of U.S. Motors is its marketing philosophy.

Perhaps the crowning achievement of USM's marketing, for its customers, has been its ability to deliver a vehicle within three working days of receiving an order for it. Allowing customers to configure their own cars, and reducing the waiting period for delivery to three days, added a new dimension to the competitiveness equation. It provided a decisive competitive advantage over imported cars and mass- produced domestic cars. More important, it radically changed the economics of automobile manufacture and marketing by eliminating inventory and its associated costs. Most important of all, the commitment to three days served as the driving force behind organizing a manufacturing system at USM that enabled it to address almost any market challenge.

USM has always prided itself on making the buying and owning of USM cars a pleasurable experience. It introduced unprecedented openness with consumers on vehicle performance and serviceability data. By calling into USMNet, consumers can receive constantly updated service and repair histories of all USM models, the prices of all vehicle models, parts and options, and estimated labor costs for repairs and servicing.

Through their own home computers, or at satellite dealer sales studios located at popular shopping sites, potential customers can design their own USM vehicle using graphic-intensive USM software. The software generates an accurate image of what the vehicle would look like as configured, as well as the purchase price and estimated operating costs for such a vehicle under the usage conditions specified.

If the customer wishes to proceed with the order, this tentative vehicle configuration can be filed on USMNet and transmitted to the nearest dealer. There, in the remarkable simulators for which USM has justly become famous, customers can experience what the car they have configured would actually feel like under various driving conditions. The first USM vehicle simulators were an early commercial adaptation of "virtual reality" gear developed by the DoD and NASA and they are always being improved by USM engineers working with simulation equipment manufacturers.

Test "drivers" settle into a programmable chair that can simulate the support of the driver and passenger seating options they have chosen. In their field of view, they see the dashboard configuration they have selected; the look of the interior given their choices of color and texture for carpeting, panels and seats; the location of all controls; the visibility through the front, rear, and side windows; and the sight lines for their choice of hood and rear deck slopes and fender shapes. They hear the engine sounds and wind noises that would be generated at whatever speed they choose to simulate, for various engine and exhaust system, as well as body shape, choices. They can listen to how the audio options will sound for given interior materials and arrangements. Through the programmable chair, the steering wheel, and the platform to which the simulated control pedals are mounted, the test "driver" feels how the suspension will react to different road surfaces and cornering speeds.

As customers proceed with their test "drive", they can adjust their functional, aesthetic, and comfort choices until they are satisfied. If they choose to proceed, they can finalize their order, with or without dealer assistance, by computer. If they wish, their order can include financing and insurance, both available through USM Corporation. USM dealers do not have a trade-in policy. A customer can arrange to sell their old car to the dealer if both can agree on a price, but this is handled as a separate transaction from the new car purchase.

U.S. Motors targeted automotive "prosumers" as its primary customers, car buyers who wanted to become actively involved in the process of customizing a car to their preferences. For this kind of buyer, the three day delivery time promised by USM was very attractive. They could have the product they had spent so much time "designing" quickly, and they could be confident that it could be redesigned as their needs or preferences changed. At the same time, by satisfying even these demanding customers, US Motor's reputation was quickly established with the car buying public as a whole.

The Department of Defense is one prosumer that takes full advantage of U.S. Motors' ability to allow customers an interactive role in vehicle design. With budgetary constraints and diversified global missions, maintaining an inventory of every conceivably necessary type of vehicle was impossible for the DoD. Through USM, the Department can reconfigure and upgrade vehicles quickly to meet changing mission requirements. It can also obtain specially configured vehicles far more quickly than under the mass production system.

In the recent "Steel Wall" alert, for example, the DoD needed to mount the newly-developed "Bull Dart" bunker-busting guided missile on 100 long range penetration vehicles. This required simulation and analysis of the structure and suspension of the vehicle for the loads involved, both in traveling and when firing on the move. Parts of the structure were strengthened and the drive train was replaced with stronger components. This was accomplished in two weeks, taking full advantage of USM's modular product design for the agile manufacturing system and its flexible fabrication capabilities. The job required intensive use of powerful computer simulators of both the vehicle and the manufacturing process, and generation of the software which converted the assembly system and other machinery to needed configurations, both at USM and its component suppliers. Intense computer interaction using enterprise integration systems between 27 organizations were another critical success factor. Without these capabilities, the project would not have been possible.

This benefit to DoD is no coincidence. In the early 1990s, DoD support for the development of agile manufacturing enterprises to meet defense production needs helped make flexible, general purpose, manufacturing machinery available to the commercial sector. It was this technology that USM was able to install in its very first factory and then offer to the DoD the kind of production services it had anticipated.

For its commercial customers, servicing a USM vehicle was designed to be as surprisingly thorough and pleasant experience as buying one. Routine maintenance, changing the oil, for example, can be performed "with a suit on". Every vehicle subassembly is tagged with a "smartchip" identifying its production history and is fully warranted against defects for the lifetime of the vehicle. On-board electronics monitor all vehicle systems and contain a current production, repair, and service history of each one and of the vehicle as a whole. The vehicle informs the owner of routine maintenance requirements based on real-time monitoring, and of pending or actual problems requiring service attention. Through the dash-mounted UltraComm, service appointments with certified dealers can be made automatically. Except for emergencies, all service is by appointment only and replacement vehicles are provided at no charge should the customer need one while service, repair, or reconfiguration of vehicle systems is performed.

Given the extremely high production quality standards observed at the three USM factories and by their suppliers, vehicle—disabling malfunctions are rare. USM cars are designed with back-up "limp home" features that allow them to be driven for up to 50 miles in the vast majority of cases. When failures do happen, components are returned to USM by the dealer for

study. Invariably, lessons are learned that lead to improvements in manufacturing, either at USM or at a supplier. In addition, customers are encouraged to comment on all aspects of vehicle performance, especially those which they feel could be improved. All customer comments are routed to appropriate USM personnel who are required to enter a response as to what action was taken, or why no action was taken.

Because they offer so many body style, interior, and equipment options, and can so easily be reconfigured after purchase, USM cars are effectively custom vehicles. They can be updated to look as contemporary as their owner wishes. They can be converted from economy to sports car specifications far less expensively than buying a new vehicle. Taking their lesson from the microcomputer markets in the 1980s and '90s, USM encouraged third-party aftermarket suppliers to offer USM-compatible equipment, sharing relevant data to promote quality products. As computer manufacturers had learned in the 1980s, the larger the third-party supplier base, the greater the longevity of the "platform" supported by those suppliers, even when newer, more capable platforms were introduced. Given the integrity of the basic vehicle design and the warranty "chip" attached to each subassembly module, it is no surprise that the resale value of USM cars is so high.

> Personal computers have been pioneering an approach to design that is bound to spread to many other complex consumer products: easy upgradeability. Tandon's new SL-III computer is actually a box with a power supply, designed to accommodate a very wide range of processor chips, hard disk drives, memory and video options. The owner can change these without opening the computer case, simply by changing cartridges, a process that does not require any tools. As one's computing needs change, there is no need to buy another computer, just upgrade.
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> IBM and AST Research, among other companies, have been offering upgradeable processors for some time, but that involves a complicated replacement operation entailing opening the computer, removing parts, installing others. Invariably, there are other technical adjustments that have to be made and the whole process is too intimidating for the average owner. Tandon's approach carries modularized components to an altogether new level: unplug one cartridge and plug in another. Modular design has other advantages as well. It will permit manufacturers to introduce improved components far more quickly than if they had to be introduced as parts of a new computer.
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> [Source: New York Times, 7/9/91]

With the intensifying environmental and energy concerns of the 1990s, the modular design and extraordinary reconfigurability of USM cars increased their appeal to many consumers. Their high resale value means that USM cars are, apart from severe accidents, never "junked". Because of their modular design and replaceable body panels, their lifetimes are extraordinary. Engines, transmissions, suspensions, brake systems, and interiors are all easily replaceable. The result is that any USM dealer will buy back any USM car from an owner, confident that it can be upgraded and sold at an attractive price. The range of engines and transmissions, including both electric and internal combustion choices, allows customers to select the power train that most efficiently meets their needs at a given period in their lives. USM was also the first manufacturer to make it practical to exchange engines as significant efficiency and emissions improvements were introduced.

Implicitly, this description of how customers see USM also contains a description of the production philosophy behind USM cars. The high degree of customizability and reconfigurability is a consequence of the modular design of USM vehicles, their system assemblies, and component subassemblies. The ability to design and profitably manufacture such a car was made possible by integrating a network of general purpose computer-controlled production machinery into a coherent manufacturing system. Developments in production machinery, manufacturing processes, and materials technologies laid the foundation for the new system. Computer control allowed for a degree of flexibility that mass production manufacturing machinery did not have. What pushed the implementation of such a post-mass production manufacturing system was the competitive environment of the early 1990s and DoD support for the formation of agile manufacturing enterprises.

The problem that U.S. automakers confronted at the start of the 1990s was selling even the significantly improved cars they were producing. The economic recession of the period notwithstanding, the Japanese automakers were offering more models, and more rapid model changes. The Japanese were experimenting on a piecemeal basis with the flexibility of the new production technologies then becoming available. They were exploring the profitability of low production-volume, "niche", cars, such as the now classic supercharged Toyota MR2 and the original Mazda Miatas, that aimed at pleasing only a certain type of buyer.

In those circumstances, it was difficult to sell essentially the same vehicle to large numbers of buyers for the three or four years necessary to pay off the production line on which that model was manufactured. Long production lines dedicated to a single model of automobile, or minor variations on it, were expensive to build, expensive to operate, and slow to change over to new models. Only by building large numbers of the same vehicles could the investment in such production facilities be recouped.

U.S. Motors came into existence committed to implementing a manufacturing system that would exploit to the fullest the most sophisticated production technologies as applied to meeting the highest customer expectations. Its managers were free to adopt whatever physical structure for the manufacturing facilities, whatever organizational structure for their management, and whatever marketing strategy seemed to them best suited to accomplishing that task.

It is tempting to say that the success of USM has come in spite of its never having manufactured more than 180,000 new cars in a calendar year, but that would be "old system" thinking. For one thing, in recent years a growing fraction of USM "production" is devoted to reconfiguring and/or updating previously manufactured vehicles, or preparing subassemblies for dealer installed upgrades. For another, the whole point of creating USM was to discover the viability of an alternative to mass production. The initial USM plant, like each of the two newer plants opened in 2001, was designed to have a maximum capacity of 60,000 cars a year, about the size of the GM production line that for decades manufactured Corvettes. But the USM plant was to be able to assemble an almost unlimited number of variations on all of its models on that same line. In addition, U.S. Motors continues to expand. Plants in Germany, France, and Japan are within six months of production and construction has begun on plants in Thailand, South Korea, and England.

Production flexibility, very rapid product development cycles —four months to the introduction of a new model as opposed to forty months under the old system—and a commitment to providing customers with significant customization options: these were to be the hallmarks of the new manufacturing system The machinery was the least troublesome item in the mix. "Intelligent" production equipment began to be available well before USM was founded and continues to become more capable. By 1995, flexible computer-numerically controlled machine tool centers, and robot assemblers, incorporating expert system diagnostic and process control software, were off-the-shelf items.

The key technical factor behind USM's success was matching the design of the vehicles it built to the capabilities of the machines that built them. Product and manufacturing process design are done concurrently. With the assistance of the first generation of hybrid supercomputers synthesizing both serial and massively parallel processors, it was possible to simulate total vehicle design as well as the process of its manufacture. A prerequisite to translating those simulations into production realities, however, was achieving complete information exchange "transparency" among all of the computers and computer-controlled devices throughout U.S. Motors.

Computer modeling eliminated the need for physical models. All of the machining tools, processing equipment, and transport and assembly systems were individually programmable, and observed a common data exchange standard, conforming to Factory America Network specifications. Thus, they could all be linked to a central computer network. The result of this integration of production machinery and the design database was that approved designs, whether of modified components or of entire vehicles, could at once be put into the production and customer order entry programs.

USM cars were designed to be modular assemblies, offering many configuration possibilities with the same manufacturability. The production lines are short, with nodes at which groups of assemblies are added. These come either from internal machining and subassembly centers, or from outside suppliers. These supplier plants are located near the USM plant and their production and delivery schedules are linked by computer to the USM production schedule data base. This required creating a single data network open to the USM "family" of companies, as well as sharing with suppliers the now familiar array of engineering and product specification tools that guarantee common precision and quality standards.

Most of the body structures in use in the early 90's could not be scaled for model variations. To deal with this, USM extended the technology pioneered in the 1980s by the Pontiac Division of GM for its Fiero model. High precision exchangeable body panels attach to a scalable structure to which module subassemblies are then attached. This allows customers to select from a variety of fender, hood, and rear deck styles at no greater cost than offering fixed styles. The modularity concept, aided by programmably adjustable tooling locators, allowed the production equipment to machine components for, and assemble in any sequence, two, four, and six seat automobiles, whether coupes, sedans or convertibles.

The same system allows U.S. Motors to offer military specification versions of its smallest and largest vehicle platforms at no more cost than the special materials called for. Utilizing the USM data exchange standard, DoD suppliers are able to fabricate specialized components to the appropriate USM module specification. The components can then be inserted directly into the USM production schedule in the same way that commercial

components are. In effect, every order for a USM vehicle, military or civilian, is a custom order. The premium paid by the DoD for its vehicles is thus reduced to the differential cost of materials, modified subassemblies, and shipping, for those DoD specialty suppliers not located near a USM facility.

On the eve of ground warfare in Kuwait and Iraq, it became clear that an extraordinary requirement existed for distinguishing friends from foes among the dense complex of air ground weaponry in the theater. One week after DARPA was given the task of identifying a solution, it did so selecting a friendly forces identification beacon proposed by Test Systems, Inc. of Hudson, New Hampshire.

The decision to follow DARPA's recommendation was made on February 13th. Five days of intensive work later, prototype units were on their way to Yuma, Arizona, for testing. Three days after that, the first 40 production units, incorporating modifications based on the Yuma tests, were en route to Saudi Arabia and 154 more were received there before the war ended. By that time, 1800 more units had been assembled by Test Systems, and almost all of the parts for assembling 10,000 more units were in hand.

Accomplishing all of this was made possible by using existing commercial industrial capacity, off-the-shelf materials, and components meeting commercial, instead of military, specifications. The critical high power light emitting diodes were commercial items, the case was plastic, and the batteries were Eveready Energizer c-cells.

Engine, transmission, and suspension subassemblies are designed so that they are easily interchangeable, as are vehicle interiors. Customers can select from a wide range of dash panels, seating arrangements, and decor/trim instead of choosing just interior color, upholstery covering, and two or four speakers for their audio systems. Furthermore, as their needs or driving preferences change, customers can at any time reconfigure many features of their USM vehicles at competitive costs: suspensions, engines, interiors, body style.

All USM vehicles can be ordered from a choice of propulsion systems, including internal combustion and electric engines in a variety of configurations. With computer-controlled delivery of components and subassemblies to assembly nodes along the line, integrated production even of such different vehicles was proved possible. Satisfying the spectrum of regulations covering engine emission and vehicle safety became easier as well as more efficient once the government set goals and allowed industry to determine the means of achieving them. With creative engineering, these goals have been reached at lower cost than was the case with mandated means. They have also resulted in vehicle systems that are much more robust and accessible to people of moderate mechanical skills. People can work on their cars again, which many USM owners in particular enjoy doing.

Product design teams are continually forming and reforming at USM, with the initiative for new projects coming sometimes from marketing, sometimes from engineering, sometimes from the production floor itself. One thing is constant. Every team reflects in its membership all of the competences required to manufacture and market a car or its subassemblies, from production line workers and engineers to supplier representatives and sales personnel. This has had a number of organizational consequences that affected the role and the style of USM management. It is a commonplace today, of course, but in 1995, USM's organizational structure was quite radical for an auto company.

The role of management at USM is to approve proposed product designs and to enable their manufacture. That is most efficiently done—and at USM, at least, that means most profitably as well—under the supervision of the product design teams themselves, suitably supported by management. Management sees to the overall coordination of manufacturing operations and to the allocation of the resources each product design team requires. Management facilitates courses of action it has approved, but these are initiated at the operational level. Rarely are they dictated from above, except for generic procedural standards. As a result, the managerial hierarchy is very flat and decision-making authority is widely distributed. This makes monitoring and coordinating plant activities a primary managerial task, along with infrastructure concerns such as contracts with suppliers, equipment servicing, work force training and education programs, and building maintenance.

Developing a sense of ownership at all organizational levels in the success of U.S. Motors, and in the unqualified excellence of its products, is central to the dynamism and the creativity of production at USM. That required a revolution in corporate cultural and managerial values that needed to be proven in practice, alongside proving the viability of an alternative to mass production. The total integration of all operational and managerial functions at USM was a given. The creation of a total information network, open to the entire work force and extending to all suppliers, was another facet of the revolution in managerial values that USM pioneered. The ruling assumption of daily operations at USM was trust in the integrity, skills, and good faith of the extended USM "family": the web of employees, suppliers, dealers, and customers that support USM operations.

Generic Agile Manufacturing Features in the U.S. Motors Scenario:

1. Commitment to "prosumer" customers supported by agile management.
2. DoD takes advantage of capability for rapid reconfiguration, reducing inventory while remaining able to react to fast-changing military challenges.
3. Commitment to customers drive the organization of technology and of management structure.
4. Product life extended through modular reconfigurability and upgradeability.
5. Complementary relationship between manufacturing process and product designs.
6. Assembly to order manufacturing.
7. Profitable low-volume manufacturing of a complex product made possible by engineering and manufacturing to close common standards distributed across vendor-supplier corporate boundaries.
8. Changes made to appropriate manufacturing equipment to achieve standardization of components, and modular, plug-compatible, designs.

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Infrastructure for the Vision

The picture of agile manufacturing described in these scenarios emerged over many hours of discussion with the inner core team. The team met two days a week, for six weeks, studying reports and listening to presentations on future directions for manufacturing. Ideas from advisory core experts were investigated, detailed, and talked through to consensus. Subsequently inner core were divided into groups in order to identify agile manufacturing enterprise characteristics, system elements and enabling subsystems for each of the scenarios in this report: the automobile industry sector, the semiconductor sector, the continuous process sector, and a multi-corporation communication product. Members rotated between groups from time to time for cross-fertilization of ideas and to share responses from colleagues back in the member's "home" corporation.

During this long, intensive, series of meetings, each of the four scenarios was analyzed, dissected and debated in depth. At the start of that detailed and intensive work, it was not at all clear that the scenarios would have similar characteristics, nor was it clear what the manufacturing systems elements would be for each of them. As the work progressed, convergence to a common set of characteristics, systems elements, and enabling subsystems manifested itself. From the many proposed items, a core set emerged as central to all the scenario sectors analyzed. This core set extended over all manufacturing. It is presented in the accompanying chart.

This material was presented during the course of the project to the outer core, over 100 senior industrial professionals who deal with manufacturing, in groups of about 20 at a time. Their responses broadened the consensus that there is indeed a common pattern of agile manufacturing systems characteristics. There is also a wide consensus that the material presented in this report is representative of the core of the infrastructure for the new manufacturing system.

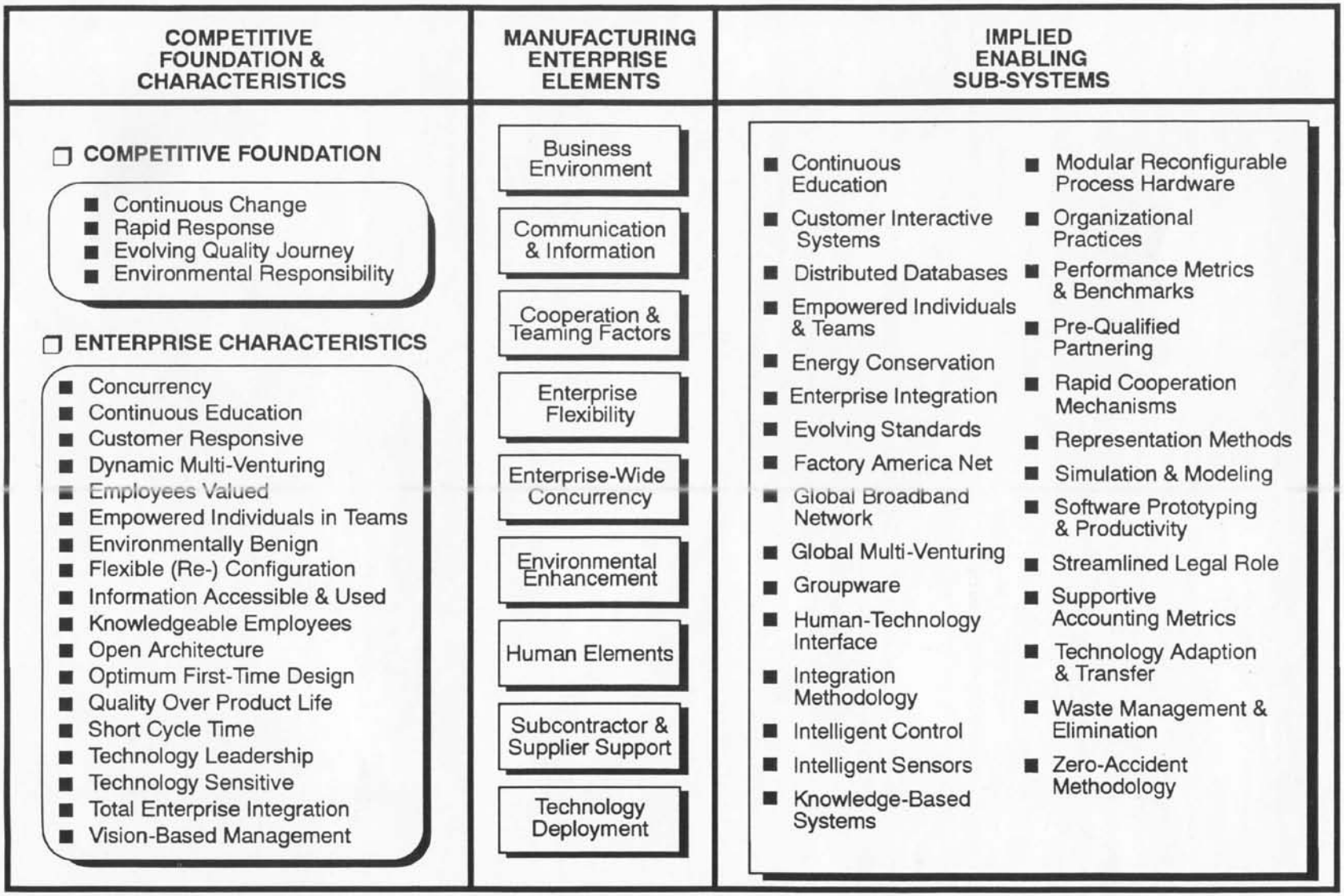
Agile manufacturing will require a new and novel infrastructure. As discussed here, the infrastructure does not include individual processes such as semiconductor fabrication details, metal removal processes and the like, important as they are. The infrastructure discussed here is that needed to support the nation-wide and corporation-wide levels of agile manufacturing systems. It can be compared to the national network of roads and highways that enables the use of automobiles and trucks. Today, many groups are occupied with designing new high performance production technologies, the cars and trucks of the manufacturing system, but little attention is being paid to the highway infrastructure. The accompanying diagram presents the essence of that infrastructure. It shows, for the competitive foundation of agility and quality, 18 characteristics needed for the agile manufacturing enterprise as a whole.

These characteristics are described in detail in Volume 2. The enterprise characteristics are supported by the nine manufacturing enterprise elements of business metrics and procedures; communication and information; cooperation and teaming factors; enterprise flexibility; enterprise-wide concurrency; environmental enhancement; human elements; subcontractor and supplier support factors; and technology deployment.

The elements of the manufacturing enterprise that support the enterprise characteristics are made possible by the enabling subsystems described in Volume 2.

Success in the new manufacturing era will be achieved only by dealing with the enterprise as a whole. It cannot be achieved by dealing only with manufacturing as narrowly viewed today. This comprehensive approach will require empowering individual workers, creating multi-function project teams, breaking down managerial hierarchies, developing and installing the required production machinery and system software. In short, the industrial corporation as a whole must change in order to achieve agility. Those companies that succeed in making the change will win; those that don't, will wither.

COMPETITIVE LEADER 2006 - THE AGILE ENTERPRISE



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COMPETITIVE LEADER 2006 - THE AGILE ENTERPRISE

COMPETITIVE FOUNDATION & CHARACTERISTICS	MANUFACTURING ENTERPRISE ELEMENTS	IMPLIED ENABLING SUB-SYSTEMS
❑ COMPETITIVE FOUNDATION ■ Continuous Change ■ Rapid Response ■ Evolving Quality Journey ■ Environmental Responsibility	Business Environment	■ Continuous Education ■ Customer Interactive Systems ■ Distributed Databases ■ Empowered Individuals & Teams ■ Energy Conservation ■ Enterprise Integration ■ Evolving Standards ■ Factory America Net ■ Global Broadband Network ■ Global Multi-Venturing ■ Groupware ■ Human-Technology Interface ■ Integration Methodology ■ Intelligent Control ■ Intelligent Sensors ■ Knowledge-Based Systems ■ Modular Reconfigurable Process Hardware ■ Organizational Practices ■ Performance Metrics & Benchmarks ■ Pre-Qualified Partnering ■ Rapid Cooperation Mechanisms ■ Representation Methods ■ Simulation & Modeling ■ Software Prototyping & Productivity ■ Streamlined Legal Role ■ Supportive Accounting Metrics ■ Technology Adaption & Transfer ■ Waste Management & Elimination ■ Zero-Accident Methodology
	Communication & Information	
	Cooperation & Teaming Factors	
❑ ENTERPRISE CHARACTERISTICS ■ Concurrency ■ Continuous Education ■ Customer Responsive ■ Dynamic Multi-Venturing ■ Employees Valued ■ Empowered Individuals in Teams ■ Environmentally Benign ■ Flexible (Re-) Configuration ■ Information Accessible & Used ■ Knowledgeable Employees ■ Open Architecture ■ Optimum First-Time Design ■ Quality Over Product Life ■ Short Cycle Time ■ Technology Leadership ■ Technology Sensitive ■ Total Enterprise Integration ■ Vision-Based Management	Enterprise Flexibility	
	Enterprise-Wide Concurrency	
	Environmental Enhancement	
	Human Elements	
	Subcontractor & Supplier Support	
	Technology Deployment	

Cooperation Mechanisms

The business environment of the twenty-first century will be characterized by the continuous introduction of new and modified products and services into highly fragmented and constantly changing markets. Speed to market will be a major competitive advantage. In such an environment, no one company will be able to possess all of the resources necessary to compete on its own. To be self-contained would imply possessing all relevant forms of expertise in the work force skill base, and maintaining all relevant production technologies.

Furthermore, there is no guaranteed competitive advantage to a company in acquiring for itself all of the resources required to produce a new product, even if it could do so. In far less time than that would take, and with little or no investment in new facilities or personnel, competitors able to utilize common data exchange standards to form an electronic inter-firm alliance, a "virtual" company, could obtain a decisive competitive position. The emerging ability to form electronic alliances in an environment of continuous innovations points to the diminishing competitiveness of vertically integrated enterprises.

The "Safari" notebook computer introduced by AT&T in the Spring of 1991 captures the spirit of such an inter-firm alliance. AT&T marketing personnel had identified a corporate market niche not being served well by the many available notebook computers. Together with AT&T engineers, they defined a set of specifications for the size, weight, and performance characteristics a machine would need in order to compete in that market. Most important, a series of upgrade paths were specified at the same time that would establish for buyers the product's longevity and its development in parallel with the likely growth of their own computer needs.

The market opportunity would long since have vanished if AT&T had to create the facilities necessary to fully design and produce such a computer on its own. Instead, AT&T management created a Safari Computer Division, linking the necessary internal managerial, sales and technical support resources. The Safari Division in turn contracted with Marubeni Trading Company to organize the machine's manufacture, utilizing Marubeni's extensive network of manufacturing sources in Japan and the Far East. Concurrently, AT&T contracted with industrial designers Henry Dreyfus Associates to create a distinctive look for the machine. Marubeni arranged for Matsushita to produce the machine, which is assembled in the U.S. out of components, almost all of which are manufactured abroad by various companies. (Interestingly, Marubeni and Matsushita belong to different Keiretsus.)

The upshot of all this activity was that four months after AT&T management decided to proceed with the product, a functional prototype was displayed at the Fall 1990 Comdex consumer electronics show and shipping began in the Spring. The immediate success of the computer with the corporate buyers it targeted was AT&T's first unqualified triumph in the personal computer market.

In addition to accelerating speed to market, inter-firm alliances can bridge fragmented markets and use generic technologies to satisfy specific customer preferences. The recent agreement among IBM, Apple, and Motorola to jointly develop an operating system and a new series of computers is an illustration of this strategy. Currently, the two largest fragments by far of the personal computer market are those served by the IBM PC "family" of computers and those served by Apple's Macintosh line. Under the new agreement, Apple and IBM will each introduce a line of computers, using a common processor chip to be manufactured by Motorola, that will be software compatible

with one another. The differences between Macintoshes and PCs will have been bridged regardless of how the computers "look and feel" to users.

Cooperative initiatives between firms, and cooperation among functionally-divided branches of the same firm, are central to agile manufacturing. The premium placed on the rapid creation, development, and marketing of new products makes cooperation inevitable.

There are many more advantages to cooperation. Cooperation allows the sharing of costs and of risks in an environment of intense competitive pressure. It permits sharing unique technological and human resources as well, and managing variable rather than fixed costs. In the course of cooperating on the solution of a common problem, a whole new body of knowledge is created out of what had been individual parts proprietary to the cooperating firms. Concurrently, by integrating their respective contributions to the whole project, a new resource is created with capabilities that had not been possessed before by the separate parts.

At the same time, interactions among highly qualified individuals with complementary expertise, focusing on a narrow, well-defined, problem are themselves stimulating. The probability is high that they will provoke innovative solutions to familiar, as well as to new, problems.

Inter-firm cooperative projects broaden the resource base for attacking a problem in parallel or in serial order, or both, as circumstances suggest. Furthermore, cooperation accelerates technology transfer among the partnering firms by their mutual adoption of relevant state-of-the-art technologies and techniques. Finally, cooperation can make a virtue out of the dependencies that even the largest firms increasingly find they develop on their suppliers' skills, on third-party suppliers of related products and services, and on the knowledgeable use of their products by customers. Cooperation can convert mutually constraining dependencies into constructive interactions that are mutually reinforcing.

Competition, as attested almost on a daily basis by business news reports of the formation of consortia, or of joint or collaborative ventures, is making cooperation between firms inevitable. The time is right, therefore, to make it easier. Three areas require attention:

(1) Elimination of obstacles to cooperation within and between firms;

(2) Elimination of social obstacles to cooperation;

(3) Implementation of the information subsystems to make easy cooperation possible.

(1) The primary virtues of cooperation are speed of response and the synthesis of new resources. Speed is enabled if the initiative to form, or to enter into, a cooperative venture is encouraged at a firm's operational level. Maintaining a lofty pyramid of managerial authority is inconsistent with such encouragement.

Without compromising its responsibilities for oversight, coordination, and allocation of resources, management must distribute authority, cultivate a relationship of trust with the work force, and combat two pernicious stereotypes. The first of these stereotypes is the inclination to devalue related work by outsiders: the not-invented-here syndrome. The second is the judgment that doing something alone is superior to doing something as part of a group: the "Lone Ranger" syndrome.

The "Lone Ranger" syndrome can impede cooperation among divisions of the same firm as well as between firms. It manifests itself as a reluctance to share knowledge and resources with others for fear of losing advantages, based on prevailing reward criteria, that would follow from succeeding alone. Significantly increasing the frequency of intra-firm, as of inter-firm, partnering agreements, will thus entail formulating new measures for identifying the cost benefits of proposed activities. Cost-based accounting measures, and cost-based managerial decision measures, that isolate parts of the firm from the whole are inadequate to recognizing the advantages of cooperation. They, too, would have to be replaced by new measures.

Another new measure that will be needed is one for evaluating the suitability of potential partner firms. Agile enterprises will have a "proactive" partnership policy, and the longevity of products designed to be indefinitely upgraded entails that the members of a partnership will change over time, as products acquire new capabilities. The ability to find reliable, effective, partners quickly requires an explicit rating scheme for partners based on something like the following set of parameters:

- Trustworthiness: reputation for honesty, integrity, morality.
- Level of relevant information the company possesses.
- Attitude toward cooperative ventures, for example, willingness to share valued resources.
- Long-term stability.
- Degree of strategic thinking by top management.

- Use and support of information/computing interface standards.
- Ability to employ scientific knowledge of relevant manufacturing processes, including computer modeling and simulation software.

With slight adjustment, these criteria can be applied both to rating corporate partners and to rating individuals for membership in intra-, as well as inter-, firm project teams. They constitute an Alpha Centauri Measure: make your choice as if you were selecting crew members on a voyage to Alpha Centauri, that is, to accompany you on a very long, constantly challenging and dangerous, voyage.

(2) Implementing technological and managerial innovations will not suffice by themselves to promote cooperation between firms. Social obstacles to cooperation must be removed, consistent with the objective of concurrently fostering competition and the competitiveness of American industry.

Creating standard cooperation models, certified in advance as legal, would go a long way toward making cooperation easier and more attractive. We have analogous models for formulating health plans and retirement funds, for wills and divorces, for forming corporations or issuing stock in a company. A company, or an individual, only needs to observe the requirements laid down in the certified model to be confident that their actions will be effective and legal.

More broadly, change is required in the prevailing attitude in American society toward anti-trust legislation, as well as in the legislation itself. The historical foundation of anti-trust legislation in the U.S. has been superceded by events. The driving concern, when this legislation was framed, in the late nineteenth and early twentieth centuries, was to protect the American public from anti-competitive practices by the then-new corporate manufacturing giants. Until the 1960s, these corporations dominated the domestic market and this domination was the foundation for the public's fears of collusion and price manipulation.

Today, the American market is a global competitive battleground in which American manufacturers have few protected positions, if any. Furthermore, the very definition of "competition" is changing. Competitors are no longer self-sufficient enterprises, as U.S. Steel and Standard Oil of New Jersey were, producing standardized products for markets where cost was the primary fact about a product. Cooperation among competitors to create products and services that satisfy individual customer preferences is now the distinctive feature of advanced manufacturing, and retailing.

Anti-trust legislation based on a conception of competition that is no longer operative loses its functionality. By inhibiting cooperation, it neither achieves the dynamic marketplace it sought to create, nor protects consumers from potential price manipulation by foreign manufacturers who control whole market segments. On the one hand, domestic U.S. legislation is inapplicable to foreign manufacturers, whose cooperative interactions are in many cases actively promoted by their governments. On the other hand, the competitiveness of American industry, at home as well as abroad, has extensive implications for the prosperity of American society. If the competitiveness of U.S. manufacturing is valuable to American society, then altering the legal environment in conformity with current realities of competition is an important policy objective.

(3) Cooperative work projects can proceed efficiently only if information can flow freely among all of the project members, however widely distributed geographically they may be.

The computers, networks, and software that distributed workers use must all be mutually compatible. Common data exchange standards must be observed across computer-numerically controlled machine tools, manufacturing-process sensors, analyzers and monitoring computers, engineering workstations, computers in production scheduling, inventory management, marketing, accounting, and research and development.

In order for products and their manufacture to be designed concurrently, another requirement of rapid response to market opportunities, by engineers distributed around the world, there must be an exhaustive, uniform electronic description of three dimensional objects and of the processes that operate on them.

Finally, there must be communication channels connecting these people and machines with one another of a capacity adequate to the volume of data that they must exchange to carry out their work.

The information technologies required for close cooperation are, or are rapidly becoming, available. The availability of groupware, that is, software designed for concurrent use by distributed groups of users, is a consequence of the spread of computer networks and of the kinds of information exchange interactions they encourage. The decisions to formulate **universal** information exchange standards, to observe them, and to install the national and international information "highways" necessary to handle expanded information traffic without bottlenecks, are more difficult. They need to be made in a way that reinforces easy cooperation.

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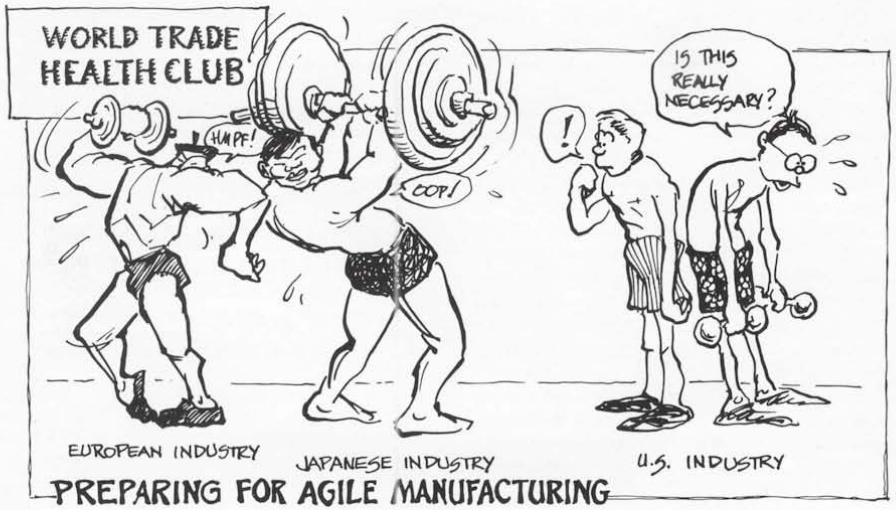
Summary and Action Agendas



The Opportunity & Vision

The industrial era dominated by mass production manufacturing is drawing to a close. It is giving way to a new era, to be dominated by agile manufacturing enterprises.

The emergence of agile manufacturing simultaneously presents U.S. industry with an opportunity to regain world manufacturing leadership and with a threat of dramatic competitive decline if the opportunity is not seized.

With agile manufacturing, competitive advantage will be determined by new criteria of quality and customer satisfaction. Highly competitive firms will develop:

- Products that are custom-designed and configured at the time of order.
- Products that can be reconfigured and upgraded to meet evolving requirements, extending product life and reducing the value of distinct product generations.
- Long-term relationships with customers who are committed to the evolving products they use, and to the companies that maintain the currency of those products.

Rapid product creation, development and modification in an agile manufacturing enterprise is made possible by:

- The routine formation of inter-disciplinary project teams, able to develop product designs and manufacturing process specifications concurrently.
- Extending the concept of design to the entire projected life cycle of a product, from initial specifications to its eventual disposal.
- The availability of scientific knowledge of the manufacturing process, and of computers capable of accurately simulating product performance characteristics, and of modeling the entire manufacturing process.
- Modular, flexible, reconfigurable, affordable production processes and equipment.
- The ability to obtain relevant information quickly, to share it with project members distributed throughout a firm and in different firms, and to link that information directly to production machinery.
- Modular product design incorporating reconfigurability and upgradability leading to extremely long product lifetimes.

The flexibility, superior process knowledge base, and focus on customer satisfaction of agile manufacturing will require assimilation of social values into the managerial decision-making process. Environmental values, energy efficiency, workplace safety and work force composition concerns, and the social impact of manufacturing enterprises will become part of agile managerial agendas.

The transition to agile manufacturing is inevitable and is already being pursued by industrial rivals of the U.S.

American prosperity is profoundly at risk unless a coordinated effort is made to enable U.S. industry to lead the global transition to the new manufacturing system.

Industry must drive the transition to agile manufacturing, but there are vital roles to be played by government and by academia in enabling, accelerating, and shaping its implementation.

No company or industry is capable of putting into place the infrastructure support systems necessary to effect this transition alone. Industry-led efforts must be supported by appropriate political action and by changes in public attitudes and institutions.

Cooperation as a Strategy for Realizing the Vision

The global economy will be characterized by continuous innovation that will reward rapid product creation and development, and increased speed-to-market. Cooperation is the factor that can dramatically accelerate innovation, product development and market distribution. Cooperation also accelerates a convergence of the respective self-interests of cooperating partners.

As a result, cooperation is central to agile manufacturing, whether in the form of cooperative ventures between different firms or different branches of the same firm.

The recent IBM-Apple-Motorola agreement illustrates how inter-firm alliances can unite fragmented markets by creating a common technological base for product variation.

Cooperation leads to sharing of:

- Risks and costs, and substitutes sharing variable costs for fixed costs.
- Unique resources, technological as well as human, in the process creating a new resource.
- Distributed, proprietary, knowledge, which in the cooperation process creates new bodies of knowledge.

Cooperation broadens the resource base for attacking problems in parallel or serial order, or both concurrently, as circumstances suggest. It accelerates technology transfer among the cooperating firms and can convert constraining dependencies of firms on one another into mutually reinforcing interactions.

Interactions among highly qualified individuals with complementary expertise working on a well-defined problem raise the probability of innovative solutions.

Cooperation between firms must be made an easier option to choose. This requires addressing potential obstacles to cooperation within firms, social obstacles to interfirm cooperation, and the information subsystems necessary to enable easy cooperation.

Anti-trust legislation no longer reflects the competitive realities of a constantly changing domestic marketplace served by global competitors. Instead, American society can benefit from encouraging electronic alliances between competing manufacturing firms.

Inter-firm cooperation will be made easier by creating pre-certified, standard models for cooperative ventures, analogous to standard models for wills, trusts, etc.

Cooperation is enhanced:

- If the initiative for cooperative ventures can be taken at the operational level.
- If management combats the not-invented-here syndrome and the cultural prejudice that values lone over team achievement.
- If management implements measures appropriate to evaluating the benefits of intra- as well as inter-firm ventures.
- If a set of criteria is articulated for rating potential project partners.

Cooperation entails the ability to share complex information electronically. Uniform data exchange standards and broadband communication channels are the necessary infrastructure for that cooperation to take place.

Information must be available to be utilized. The creation of a national industrial data base of products, facilities, and services along with price, performance characteristics, that is, a Factory America Network (FAN), would be a resource of the first order.

Building & Maintaining Momentum

The transformation of manufacturing that is underway is a dynamic process, one that will be shaped in part by unforeseeable developments. It is also a process that requires a supporting infrastructure that can only be created through a coordinated, cooperative, effort on the parts of industry, government, academe, and society at large. Furthermore, the new manufacturing system that is coming into being is one characterized by routine, intensive collaborations among personnel distributed across, as well as within, firms.

To accomplish the transition to agile manufacturing effectively, a mechanism is needed that will, on a continuing basis:

- Measure the value of decisions taken against the evolution of manufacturing from mass production to agile production.
- Promote a national consensus on the need for a competitive manufacturing apparatus and coordinate identification of the infrastructure requirements for an agile manufacturing system.
- Facilitate routine collaborations among manufacturing enterprise personnel as a means of achieving agility

All of these activities come within the purview of an Agile Manufacturing Forum whose formation is an outcome of the 21st Century Manufacturing Enterprise Strategy effort. The broad objectives of the Forum are to organize an agile manufacturing constituency, to build momentum on behalf of a common national vision of agile manufacturing, and to translate this momentum into action in order to accelerate the realization of that vision in the U.S. (See the Agile Manufacturing Forum box for more details.)

The Agile Manufacturing Forum will not supplant existing organizations concerned with manufacturing. Its operational mission is to coordinate the focusing of relevant resources of those organizations on the successful accomplishment of agile manufacturing initiatives. By not having direct responsibility for projects it will maintain an independent and unbiased overview of progress towards agile manufacturing. Its structure will take the form of a centrally coordinated network of regional forums with membership open, and accessible, to small- and medium-sized enterprises, as well as to large ones. Because of the benefits to the Department of Defense of a mature, U.S.-based agile manufacturing system, the active involvement of the DoD in creating the Forum, in partnership with industry, supporting it through its formative phase, and in participating in its projects is especially important.

The following action agendas incorporate, in addition to the conclusions of the 21st Century Manufacturing Enterprise Strategy study group, recommendations drawn from the Council on Competitiveness report "Gaining New Ground" and the Center for Strategic and International Studies report "Integrating Commercial and Military Technology for National Strength".

What Should Industry Do?

The choice confronting U.S. industry is simple to describe, but difficult to make. Individual companies can pursue the transition to agile manufacturing on their own, or as part of a coordinated national effort, but they must pursue it. The first choice feeds a number of American stereotypes championing self-sufficiency, but, in truth, it is no choice at all. Agile manufacturing as a system is keyed to institutional interdependencies that reward individual initiative in creating new resources out of those very interdependencies. Cooperation in the context of agile manufacturing is much more than a prudent strategy for management to adopt. It is an expression of the distinctive genius of the agile manufacturing system.

The recent increase in the pace of formation of cooperative ventures among traditional competitors, as well as among companies with complementary resources, is symptomatic of the dynamism of agile manufacturing competition already at work. It is becoming obvious to wider circles of industry executives, policy makers, politicians, and educators that flexible, spontaneous, inter-enterprise cooperation is a formidable competitive weapon. The difficulty of forging that competitive weapon is, however, equally formidable. This is particularly so in the U.S., where the infrastructure requirements for agile manufacturing are only partially developed and where cooperation traditionally is a preferred managerial option only in times of crisis.

The only real choice for U.S. industry, then, is to lead a national effort to erect the infrastructure

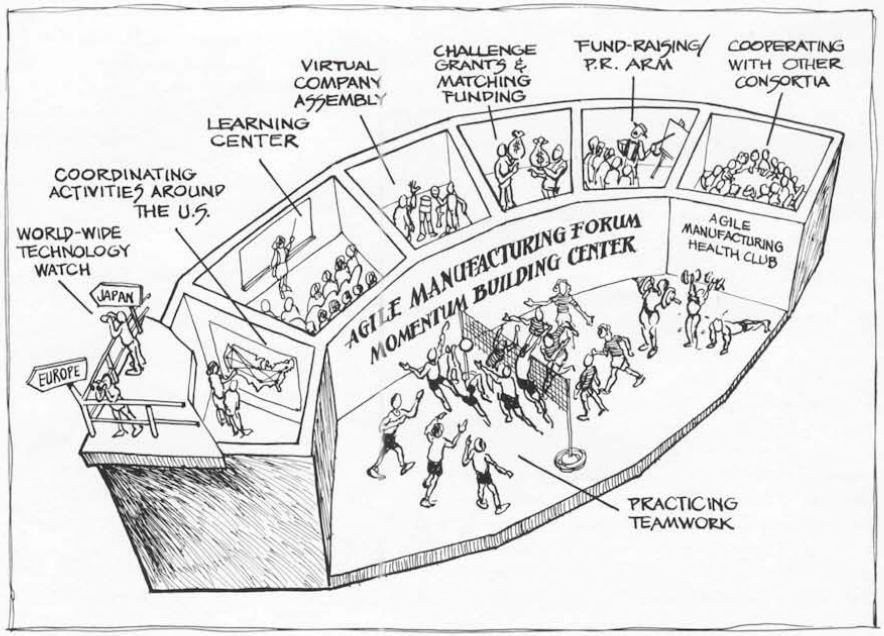
requirements for agile manufacturing on a foundation of systematic cooperation.

The objective of this effort is for inter-enterprise cooperation to be as natural and as straightforward as connecting together components for a home audio and video system made by different manufacturers and purchased at different stores. If the U.S. is to achieve leadership in the transition to agile manufacturing, then industry must aggressively pursue that objective. Industry must put into place intra-firm programs consistent with agile manufacturing. Industry must also implement mechanisms, such as the Agile Manufacturing Forum, for making interfirm cooperation natural. Industry must actively promote the necessary supporting contributions from government, society, and academe.

Industry must take the lead; and, it can take the following steps on its own:

Adopt methods and procedures to transform the enterprise into an agile manufacturing competitor able to compete in the global marketplace successfully, today and in the future.

- Continuously improve the quality of the enterprise by constantly advancing the criteria by which quality is measured.
- Extend and amplify the pull of customer satisfaction throughout the enterprise.
- Remove organizational obstacles within companies to the formation of cooperative ventures.
- Pursue concurrency within and between enterprises, cooperating with academe on identifying the technological and organizational requirements, and establishing their effectiveness.



- Identify cycle time reduction opportunities for all enterprise activities and actively pursue their development.
- Develop intimate, responsive, supplier-vendor-customer networks, incorporating interactive information exchange systems as appropriate.
- Empower the work force at all levels of the enterprise; and involve the work force in setting company agendas and in exercising initiative to accomplish them.
- Develop metrics that will measure the value of the work force as a corporate asset. Use these metrics to define the need for, and invest in, continuous work force training and education.
- Assimilate into the managerial decision-making process, as an expression of corporate responsibility independent of local laws, public concerns about the environmental and social impacts of manufacturing, energy usage and conservation, workplace safety, and work force constitution.
- Identify the generic technological and organizational requirements for making the transition from flexible to agile manufacturing.
- Identify regulatory and legal barriers to the formation of cooperative ventures and pursue their removal.
- Identify infrastructure requirements that will enhance distributed concurrent product control, development and manufacture.
- Articulate the requirements for comprehensive manufacturing information exchange standards. Draw up specifications for these standards cooperatively with government and expand representation of the U.S. on international standards bodies.
- Define the requirements for a global broadband communications network, promoting to government and the public its strategic importance to the nation's well-being.
- Identify jointly with academe, the characteristics of a competitive manufacturing work force and develop educational vehicles for achieving it.
- Identify, develop and evaluate the effectiveness of metrics appropriate to the management of agile manufacturing enterprises.

Establish effective interfirm cooperation and partnership mechanisms among U.S. industry groups through the formation of an Agile Manufacturing Forum. Actively promote the necessary supporting contributions to the Forum from government, from industry, society, and academe. The Agile Manufacturing Forum should:

- Be a mechanism to define agile manufacturing infrastructure projects, and to form groups willing to cooperate in each project.
- Use challenge grants and other incentive mechanisms to encourage groups to form, define and develop infrastructure projects.
- Work with existing consortia and other professional groups to promote and develop cooperative mechanisms.
- Conduct meetings, workshops, and briefings around the country to build momentum toward implementing agile manufacturing cooperation mechanisms.
- Serve as a central resource that can coordinate efforts, provide a clearinghouse function, help replicate regional efforts, maintain data bases, and provide other related services to foster the rapid spread and development of infrastructure partnerships and cooperation projects.

Examples of the type of cooperative projects that may be undertaken are defined in the Infrastructure volume of this report. Some generic examples of these are listed below:

- Formulate standard models for initiating cooperative ventures.
- Develop requirements and metrics for cooperation tools, and sharing the cost of developing cooperation tools, along with government and academe.
- Develop environmentally benign manufacturing processes in cooperation with government and academe.
- Create jointly with the government a Factory America Network as a high priority agile manufacturing infrastructure element.
- Simplify manufacturing-related standards "architectures", making them more reliable and extendable.

- Establish practical near-term implementation criteria for cooperative industrial, government and academic R&D in agile manufacturing.
- Develop jointly with government and academe, technology deployment measures.
- Extend distributed concurrency globally, and extend FAN to a World Manufacturing Network, identifying the advantages of this extension to U.S. manufacturers, and criteria for success.

What Should the Congress Do?

Recognize the importance of manufacturing to U.S. industrial competitiveness and to advancing the nation's standard of living.

- Promote the excellence of U.S. industry as a national asset and protect the health of the nation's small suppliers.
- Support industry investment in continuous work force training and education.
- Mandate the coordination of existing manufacturing support programs in government agencies.

Create a U.S. economic & regulatory climate that encourages investment in agile manufacturing.

- Facilitate the transition to agile manufacturing by removing legislative and regulatory barriers to cooperative R&D, carried through to production floor demonstrations, to multi-enterprise manufacturing ventures, and to the formation of virtual companies.
- Remove any mandated performance-metric requirements that discourage concurrent engineering and agile enterprise management.
- Approve standard legal models for cooperative manufacturing venture formation.
- Adjust anti-trust legislation, and corporate reporting requirements, to reflect current competitive realities and the emergence of agile enterprises.
- Support adoption by industry of environmentally benign manufacturing as a goal by establishing uniform environmental legislation, simplified compliance procedures, and protection from environmentally abusive foreign manufacturers.
- Make the cost of capital for the development of manufacturing technologies competitive with that of America's major competitors.
- Accelerate depreciation schedules and capital cost-recovery programs for manufacturing equipment and facilities so that they are competitive internationally.
- Make an R&D tax credit permanent and amend it to include manufacturing engineering and process R&D.
- Make the federal government a discriminating customer of manufactured products, by comparing and benchmarking against companies, other government agencies and foreign governments.

Invest in the infrastructure and the technology required to speed the transition to agile manufacturing.

- Establish a five-year graduated plan to increase federal R&D expenditures for critical infrastructure and manufacturing technologies, if necessary, by restructuring funding schedules for existing programs.
- Increase investment in manufacturing at an earlier point in the R&D cycle, concurrent with the development of new product technologies. Investment in manufacturing should be matched to the collective needs of the industrial base.
- Implement decisions to make sure that the federal laboratories' contribution to agile manufacturing is as high as possible and commensurate with the annual national investment of $20 billion in the over 700 federal laboratories.

Ensure that America has a world-class manufacturing infrastructure, supported by both physical assets and human resources.

- Mandate the creation and full development of a national broadband communication and information network.
- Recognize the value of FAN and fund a government share in creating it.

The Agile Manufacturing Forum

The Agile Manufacturing Forum will not supplant existing organizations concerned with manufacturing. Its operational mission is to coordinate the focusing of relevant resources of those organizations on the successful accomplishment of agile manufacturing initiatives. By not having direct responsibility for projects it will maintain an independent and unbiased overview of progress towards agile manufacturing.

The activities of the Forum will include:

- Pursuing a national consensus on the nature of agile manufacturing. This will serve as a prelude to articulating project proposal criteria that will advance the implementation of agile manufacturing.
- Developing and administering a Department of Defense-initiated Challenge Grant program in support of agile manufacturing technologies, processes, infrastructure elements, and managerial practices. DoD funds are to be leveraged at least 2:1.
- Developing and administering a Manufacturing America Foundation, a tax-exempt entity devoted to advancing public appreciation of the importance of a competitive manufacturing sector to national prosperity.
- Providing supplementary resources, including model mechanisms and facilitators, to personnel in firms wishing to introduce agile manufacturing initiatives.
- Maintaining industry leadership of the transition to agile manufacturing while coordinating the agile manufacturing agenda with concerned government agencies, with academe, and with appropriate public interest groups.
- Conducting workshops to advance the state-of-the-agile manufacturing art, to identify new project areas, and to recruit Forum members.
- Providing services to Forum members such as:
  - Creating model certification agreements which embody relevant cooperation commitments, thereby simplifying the identification of desirable partners for the creation of virtual companies.
  - Coordinating continuing joint projects.
  - Providing linkages to existing manufacturing organizations to assist Forum members in organizing joint projects.
  - Facilitating the formation of, and investment in, joint ventures.
  - Outreach services that promote agile manufacturing as a system.
  - Providing centralized facilities to assist in the organization of conferences and workshops to continue to build consensus for agile manufacturing.
  - Maintaining a manufacturing enterprise network and data base.
  - Generating resource materials, including a textbook on agile manufacturing, project "kits" to assist in implementing agile manufacturing initiatives, and a newsletter.

- Support the formation of national and international information and communication exchange standards, funding U.S. standards maintenance and representation on international standards councils.

What Should the DoD Do?

There are four reasons why the Department of Defense should be an active partner with U.S. industry in accelerating the implementation of an agile manufacturing capability.

(1) The transition to agile manufacturing is already underway in non-defense industry. If DoD is not actively involved in matching its requirements to the character of the new system, it will lose on two counts:
  - it will not gain the benefits promised by agile manufacturing;
  - it will have to support a parallel manufacturing apparatus that lacks effective competitive capabilities.

(2) By accelerating the implementation of agile manufacturing, DoD will reduce the costs of products made for the DoD.

(3) Agile manufacturing is keyed to customized production. There is no added cost for satisfying customers with special requirements.

(4) Changing mission requirements can be met by rapid reconfiguration of existing equipment, conferring significant logistical and battlefield advantages.

Reconfigurability and upgradability are generic features of agile manufacturing products. If DoD requirements can be satisfied by products whose specifications lie within the range of configurability of commercial production facilities, substantial savings can be realized. In addition, the modular and scalable architecture of agile manufacturing facilities provides the kind of surge capacity that will reduce the need for special DoD manufacturing, or remanufacturing, facilities. Agile manufacturing products have extended lifetimes through designed-in reconfigurability and upgradability. This is an invaluable asset in an era of rapidly changing, diverse, DoD missions.

For DoD to reap the benefits of agile manufacturing, two conditions must be met:

- Agile manufacturing must be the norm for commercial products.
- DoD must be a cooperating customer, familiar with, and involved in, agile manufacturing design and production practices.

Cooperation permits the creation of new resources by synthesizing them out of existing inputs from varied sources, no one of which could, or could rapidly and cost-effectively, create that resource. Utilizing a national industrial data base and the device of "virtual" companies, for example, the expertise and the facilities necessary to design, test, and manufacture new, or improved, products can be assembled quickly. The need for constructing new production facilities is minimized.

The prospect of rapidly developed defense products, of extensive configuration options, simplified reconfiguration and upgrade capabilities, and much lower costs for satisfying special DoD requirements, makes a compelling case for a DoD stake in the implementation of agile manufacturing. To protect and to advance its interests, the Department of Defense should create incentives for the commercial implementation of agile manufacturing.

The DoD should:

- Take appropriate steps to encourage the widespread use of cooperation and partnership mechanisms by industry in working with DoD.
- Take strong steps to eliminate the perception and or reality of an adversarial relationship between industry and the DoD.
- Establish an expectation of partnership relationships between DoD and industry by giving preference to project contracts with shared risks, burdens, and benefits.
- Fund multi-enterprise (virtual company) projects.
- Establish mechanisms within DoD that promote cooperative venture DoD contracts, leveraging DoD resources.

The DoD should follow the practices of agile manufacturing in its own operations, by adopting industry practices and commercial standards where ever possible. The use of special military standards and specifications should be minimized.

- Emulate the close relationship between manufacturers and suppliers in agile manufacturing by strengthening DoD links with its tier of suppliers.
- Cooperate with industry in the development of the agile manufacturing infrastructure, and ensure that developments are compatible with DoD needs.
- Require uniform product description standards for DoD contracts, thereby supporting information infrastructure systems such as CALS, PDES, et cetera.
- Support the formulation and implementation of universal data/information exchange standards.
- Drastically reduce the number of non-commercial standards used in DoD manufacturing operations.

Remove impediments to the transition to, and practice of, agile manufacturing in DOD operations, regulations and practices.

- Remove barriers to the integration of commercial and military manufacturing, especially:
  —cost accounting requirements;
  —military specifications/standards;
  —intellectual rights in technical data;
  —unique contract requirements.
- Give industry leeway to alter procedures and set performance metrics in accordance with the evolving character of the new manufacturing system, adapting DoD requirements appropriately.
- Remove barriers to the adoption by industry of accounting and management metrics appropriate to agile manufacturing. For example, remove barriers to company investment in work force training and education.
- Increase and extend manufacturing development funding to include pilot production runs and manufacturing process technologies, as well as the required infrastructure.

Promote and invest in the transition to agile manufacturing with industry to ensure benefits for DoD.

- The DoD should accelerate the commercial implementation of agile manufacturing supporting the creation of the Agile Manufacturing Forum, and participating with industry in Forum activities.
- Use the Agile Manufacturing Forum as a means of immediately establishing a challenge grant program for industry-proposed projects for the transition to agile manufacturing that would leverage DoD funding by at least two to one.
- Promote distributed enterprise integration by defense contractors.

Military commanders in the 21st century are likely to find themselves fighting far from home, confronting unforeseen conditions, and leading forces high in technology and low in numbers. Brushfire wars and strike force assistance to allies are likely scenarios. Political pressures at home for quick results with few casualties will further constrain strategic options. Defense budgets will never be large enough to permit the services to stockpile every type of weapon they may need against every possible contingency. If the United States desires to project a credible military force abroad, it must create an industrial manufacturing base that can quickly produce the right weapons at the right time.

The field commander will be the customer of tomorrow's battlefield. We need an industrial base that can quickly and economically put high performance equipment into the hands of those customers. Orders for specialized weapons must be developed within a global communications network that will allow a commander to see and "test drive" alternative simulations of his equipment demands. On-line, continual feedback between field officers, engineers and contractors should force a workable design within day, or at most, weeks. Acquisition would proceed in parallel. Production contracts would be completed as the design evolved.

The Bunker Bomb Story: A Case In Point

Thirty-seven days after U.S. Air Force officials circulated a request for help in destroying Iraqi command bunkers that had survived direct hits from 2000 pound bombs, GBU-28 eliminated Bunker No. 1 at Al-Taji Air Base. Texas Instruments, Lockheed and Eglin Air Force Base personnel created, in 37 days, a high technology weapon of unprecedented penetrating power that would ordinarily have taken at least 18 months to develop.

On January 21, 1991, the Air Force in effect gave TI, Lockheed, and its own project staff a free hand to get the job done as quickly as possible, and worry about paperwork and bureaucratic channels later. A Lockheed employee remembered reading about the stockpiling of old gun barrels. The barrels were located at the Letterkenny Arsenal in Pennsylvania and Eglin personnel soon had a shipment of 8-inch howitzer barrels en route to Watervliet Arsenal in New York without waiting for approval. By February 1st, Army machinists at the arsenal were machining the barrels into what would become the bodies of the new bombs.

Lockheed's job was the warhead. Texas Instruments' job was the guidance units. On February 12th, before the Air Force had settled on a final bomb design, let alone a contract, TI officials took a chance and booked the only available useful time on the Dallas—based LTV Aerospace wind tunnel, over the weekend of Feb. 16-17. They had four days to build a quarter-scale model of the bomb, set it up to test body and tail fin configuration and develop guidance software to achieve pinpoint accuracy with a bomb that existed only as a computer model.

The TI engineers worked in teams throughout the weekend, generating what they hoped would be successful data. Monday morning they began feeding that data into computer simulations. On Thursday, at the Air Force's insistence, two completed sets of guidance units were shipped to Eglin before TI engineers had performed their own final tests. Two more sets were requested for Nellis Air Force Base in Nevada just as soon as those tests were done. That turned out to be Saturday, Feb. 22nd.

Sunday morning, one inert bomb was test dropped on the Tonopah Test Range and penetrated over 100 feet into the ground. On Tuesday, the second bomb penetrated more than twenty-two feet of concrete at a Holloman, New Mexico test. Hours before that test, however, Eglin personnel had filled the warheads of their two units with explosives. They were immediately flown to Saudi Arabia where, less than eight hours after their arrival, they were on their way to a rendezvous with Bunker No. 1.

[Source: Dallas Morning News, 6/30/91]

- Support research to identify the system elements of distributed concurrent engineering and promote their maturation.
- Share in the creation of Factory America Network (FAN) and in the installation of the broadband communications channels required by FAN.
- Accelerate industry's adoption of the goal of environmentally benign manufacturing by sharing in the development of the technologies required for its accomplishment.
- Use defense production projects as vehicles for continuing to identify the core elements of agile manufacturing and then supporting research into these jointly with industry and academe.

What Should the Executive Branch Do?

Apart from the Department of Defense, various Executive branch agencies have important contributions to make in realizing the vision of an agile U.S. manufacturing apparatus.

Take the lead in establishing the competitiveness of the manufacturing sector as a national priority because of the dependence of the standard of living on its wealth generation capability.

- Communicate to the public the importance to U.S. competitiveness of the transition to agile manufacturing and its relationship to the national standard of living. Involve key policy makers more closely in these issues.
- Highlight the priority of manufacturing technology in the annual State of the Union message.
- Make research on generic industrial technologies a national R&D priority.
- Identify the skill base of the work force as the nation's most valuable asset.
- Expand the focus of the National Security Council to include issues related to manufacturing and industrial competitiveness.

Develop policies and programs to ensure that America has a world-class agile manufacturing infrastructure.

- Support the extension of national and international broadband communication networks.
- Promote public education and provide incentives to make technical education and careers in manufacturing more attractive to the brightest young people.
- Create incentives for industry investment in continuous work force training and education.
- Support the creation of a national industrial information network, Factory America Network (FAN).
- Create an award, or awards, similar to the Malcolm Baldrige Award to recognize manufacturing companies that assimilate social concerns such as the environment into their managerial agendas.
- Support removal of legislative and regulatory barriers to the routine formation of virtual companies.
- Take steps to accelerate the pace of technology transfer.

What Should Academe Do?

The speed and effectiveness of the transition to agile manufacturing will be dependent on significant action by the academic community at all levels. There are three driving factors behind this dependence. In what follows we identify the driving factor and what academe should do.

In response to the dependence of agile manufacturing on the skill base of the work force, academe should:

- Help identify metrics and methods of utilizing human resources to maximum competitive advantage.
- Develop, cooperatively with industry, appropriate life long training and education curricula.
- Develop and provide educational vehicles for delivering life-long, continuous, work force training and education.
- Institute continuous curriculum review and reform in science and engineering education, and in business and management education, in support of agile manufacturing.
- Develop or significantly strengthen undergraduate curriculum leading to careers in manufacturing.
- Work aggressively with industry to ensure that science and engineering curricula reflect the interdisciplinary requirements of agile manufacturing enterprises.

Provide traditional academic research and collaboration on agile manufacturing. For example, conduct research in the following areas:

- Design and maintenance of information exchange standards.
- Articulate the requirements for:
  - —implementing concurrent engineering, along with mechanisms and metrics for evaluating their effectiveness;
  - —enterprise integration implementation;
  - —cooperative mechanisms within and between firms and measures for evaluating their effectiveness;
  - —forming virtual companies;
  - —operational level work force empowerment;
- Environmentally benign manufacturing practices;
- Design of broadband communication networks;
- Distributed data bases;
- Design and support of cooperation tools.

In addition to the more traditional roles above, academe has an important new role to play in facilitating the creation of agile manufacturing enterprises. Academe must:

- Act as a facilitator for, and partner in, government and industry cooperation in the Agile Manufacturing Forum, helping to speed the development, and assessing the progress of agile manufacturing in the United States.
- Recognize its impact as an economic development agent.
- Clarify the impact of standards and/or the lack of standards on the transition to agile manufacturing.
- Provide support for the development of dynamic standards able to evolve over time as requirements change.
- Participate in the creation of Factory America Network and its underlying technological and organizational infrastructure.
- Help shorten the time for technology transfer.
- Enhance vocational-technical secondary school, and two-year college, business and technical education.
- Contribute significant resources to improve primary school education and to develop measures of improvement.
- Conduct strategic planning by educational institutions at all levels in conjunction with industrial partners.
- Highlight career opportunities in agile manufacturing. Take steps to excite young people at the formative stages of career planning. Provide teachers and other community members with support in explaining the importance and excitement of a career in an agile manufacturing enterprise.

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Task Description

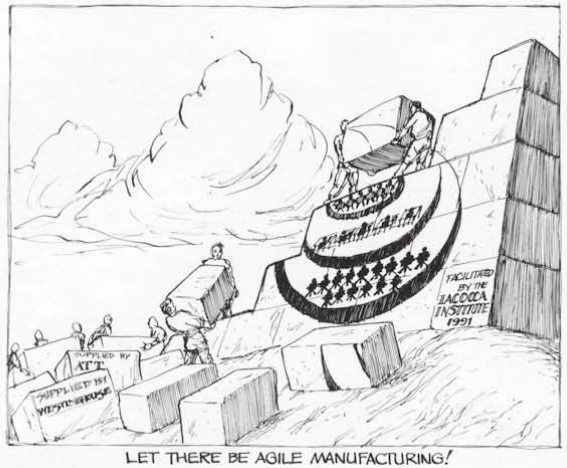
The defense authorization bill for 1991 directed the Secretary of Defense to submit to Congress a National Defense Manufacturing Plan. Accordingly, Undersecretary of Defense Donald J. Yockey appointed a broad-based government agency task force to prepare such a plan. In addition, the Iacocca Institute at Lehigh University was asked by the Office of the Secretary of Defense (OSD) MANTECH program office to organize an industry-led response to the Congressional directive.

The focus of the project was the direction in which advanced manufacturing was moving today and the opportunity this presented for U.S. industry if a concerted effort were made to exploit that opportunity. The parameters of the project, were:

- That the vision drawn of manufacturing in fifteen years be drawn from the many excellent reports recently published and reflect a consensus of a broad spectrum of experts, not the predictions of the project members;
- That the vision address the infrastructure of manufacturing in 2006, as well as the subsystems required to support the infrastructure, but not the underlying manufacturing process technologies.

The 21st Century Manufacturing Enterprise Strategy project was led by industry in coordination with the Department of Defense. The expenses of the industry participants, including salaries and all travel and living expenses over a period of three months, were paid by industry. This represents a major commitment on the part of 13 corporations who contributed manufacturing executives to the project's inner core. In addition, executives from over 100 additional companies participated, at company expense, in two rounds of interaction with the ongoing work of the inner core. The responses of these participants materially influenced the outcome of the project.

The Iacocca Institute's approach to this project was to create a three-tiered executive vehicle. The first tier was an inner core team of high-level manufacturing executives, together with Department of Defense representatives, who over a period of five and one-half months would meet in intense sessions at Lehigh University and who were supported by university faculty, staff and researchers.



LET THERE BE AGILE MANUFACTURING!

The second tier was an advisory core, a group of experts in various fields of manufacturing technology, vision creation, and cooperation mechanisms among industry partners, who would address these and other critical issues.

Lastly there would be an outer core of high-level industry executives with whom the preliminary draft of the inner and advisory core's sessions would be shared for review and feedback in an executive briefing/mini-workshop format. Following these workshops, the preliminary draft would then be revised and edited, and once again presented to the outer core for further review.

The Approach:

- The Iacocca Institute of Lehigh University would facilitate pursuit of the vision, provide leadership, and coordinate the activities of various core members, as well as provide research capability and staff support.
- The inner core team, listed below, would consist of manufacturing executives whose task it would be to formulate a structured vision and enterprise strategy and to recommend a continuation mechanism to implement that strategy.
- The project strategy was to start with existing visions and other documents to gain the benefit of prior work, and in

order to reach rapid consensus among inner core team members on the vision advanced.

- Hundreds of reports and source documents were screened by the research staff to provide the inner core with the most current and insightful reading material. Twelve examples are listed under "Selected resources studied by the Inner Core" on the following pages.
- The inner core would use an advisory core, again listed, of selected executives as subject matter experts for briefings as required.
- The inner core team would share its preliminary plans with industry executives and involve this broader outer core of executives, listed by organization, in executive briefings/mini-workshops to provide critical review and feedback during the task.
- The inner core team would then adopt where appropriate, or reply to, the outer core critique in order to provide both the sense and the fact of participation and ownership of the vision to outer core members.
- Acting in concert with inner core team members as well as other participants in the project, project team members would then work to obtain CEO endorsement of the vision and framework, as well as commitment, to maintain the momentum.

Differences from prior approaches:

- Project led by industry.
- The vision and other activities were centered around searching out the best reports and forming a convergent view, rather than "starting over."
- This project is action oriented. A primary focus is on securing a corporate buy-in at the highest levels of industry to the vision and to the concept of cooperation in carrying out the recommendations.
- A continuation mechanism is defined: see the Agile Manufacturing Forum described in the previous chapter.

Advisory Core subject matter experts:

- Steven V. Balint, Assistant Deputy Chief of Staff for Weapons Systems Production Management, U. S. Army
- Steve Bomba, Vice President, Technology, Johnson Controls
- David W. Cheney, Senior Associate, Council on Competitiveness
- Philip Francis, Vice President, Corporate Technology Center, Square D
- Robert W. Hall, Editor-in-Chief, Target
- Richard H. F. Jackson, Deputy Director, Manufacturing Engineering Laboratory, National Institute of Standards and Technology
- Ben Kaminski, President, CAM - I
- Michael J. Kelly, Director, Defense Manufacturing Office, Defense Advanced Research Projects Agency
- Charles Kimzey, Assistant for Manufacturing Technology, Office of the Secretary of Defense
- George Kuper, President, Industrial Technology Institute
- David Lando, Vice President, AT&T
- Mark S. Lang, Executive Director, Ben Franklin Advanced Technology Center
- Peter W. Likins, President, Lehigh University
- Steven M. Linder, Director of Production Assessment Division, Office of the Assistant Secretary of the Navy
- James Ling, President, Ling Technologies, Inc.
- Thomas Mahoney, Acting Executive Director, Manufacturing Studies Board
- Lt. Col. Erik Mettala, Program Manager, Defense Advanced Research Projects Agency
- William S. Safier, Director, Naval Industrial Resources Support Activity, United States Navy
- Charles L. Strecker, Manufacturing Technology Directorate, Electronics Division, Wright Laboratory, United States Air Force
- Barry Whalen, Vice President, MCC

Representative resources studied by the Inner Core:

- "Can Small Business Help Countries Compete?" (Howard) **Harvard Business Review** Nov/Dec '90
- **Department of Defense Critical Technologies Plan**, 1991.
- "Does Corporate Nationality Matter" (Reich) **Issues in Science and Technology** Winter '90-'91
- "Future Factory System Formulated in Japan (2)"(Suda) **Techno Japan**, Vol. 22(10), October 1989.
- **Gaining New Ground: Technology Priorities for America's Future**, Council on Competitiveness, 1991
- **Integrating Commercial and Military Technologies for National Strength: An Agenda for Change (Van Opstal)** Report of the CSIS Steering Committee On Security and Technology.
- **Manufacturing 21 Report - the Future of Japanese Manufacturing,** Association for Manufacturing Excellence, 1991.
- **Report of the National Critical Technologies Panel,** National Critical Technologies Panel, 1991
- "Strategic Intent" (Hamel & Prahalad) **Harvard Business Review** May/June '89
- **U.S. Defense Industry - Key Issues for the 1990s**, Ernst & Young, Oct. '89
- "Who Is Them" (Reich) **Harvard Business Review** Mar/Apr '90
- "Who Is Us" (Reich) **Harvard Business Review** Jan/Feb '90

Selected Advisory Core Topics:

- Air Force Microelectronics Manufacturing Science and Technology (MMST)
- ATP Program as Mechanism
- Business of Paradigms, The: Discovering the Future (video tape)
- Council on Competitiveness Report, Gaining New Ground: Technology Priorities for America's Future:
- Defense Advanced Research Projects Agency: Manufacturing and Design Engineering in Ultra Reliable Systems Acquisition for Devices on Demand; and "Micro Tech 2000".
- Department of Defense MANTECH Program
- IMS as a Possible Framework Model
- ITI Experience with Mechanisms
- LINC as a Concept for a Mechanism
- Manufacturing Studies Board Reports
- Manufacturing 21 Report
- MCC as a Mechanism
- NCMS as a Mechanism
- Power of Vision, The: Discovering the Future (video tape)
- U. S. Memories as a Case Study
- White House Office of Scientific and Technology Programs
- Critical Technologies Report

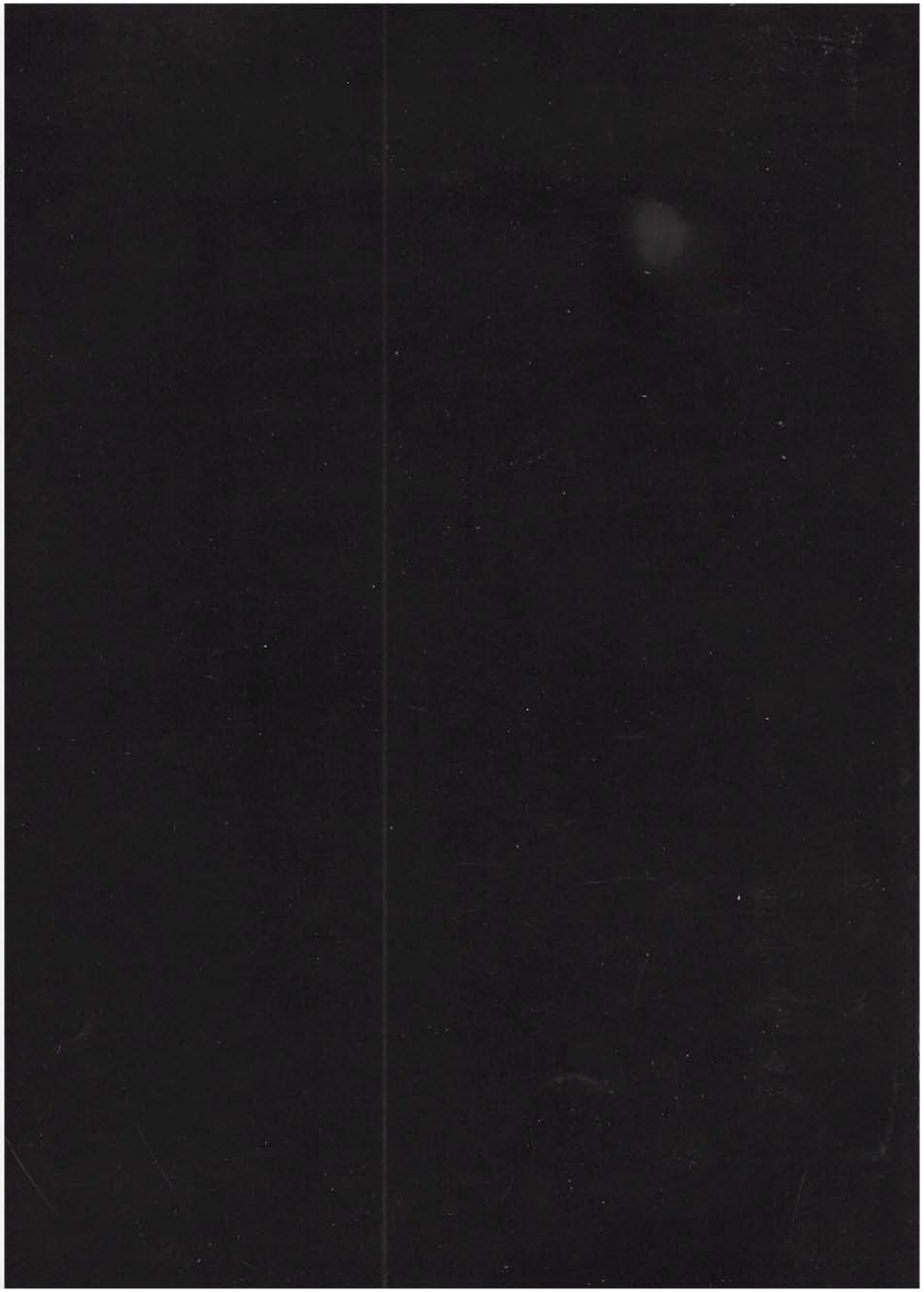
Outer Core organizations who hosted workshop briefings:

- Aerospace Industries Association
- Computer Aided Manufacturing-International (CAM-I)
- Council on Competitiveness
- Defense Science Board Summer Program
- Industrial Research Institute, Inc.
- IC² - Innovation, Creativity, Capital
- Microelectronics and Computer Technology Corporation
- National Machine Tool Builders Association
- National Academy of Engineering
- National Center for Manufacturing Science
- National Institute of Standards and Technology

Outer Core organizations represented at workshops:

- Allen-Bradley
- Allied Signal Aerospace
- Aluminum Company of America
- Applied Materials
- Babcock & Wilcox
- Bethlehem Steel
- Bodine Corporation
- Boeing Computer Services
- Bridgeport Machines Inc.
- Brown & Sharpe Manufacturing Company
- Burdeshaw Associates, Lt.
- CAM-I, Inc.
- Carnahan & Associates
- Carnegie Mellon University
- Carnegie Institute of Technology
- Carpenter Technology Corporation
- Cincinnati Milacron
- Citibank
- CompuAdd
- Council For Equal Business Opportunity, Inc.
- David Taylor Research Center
- David Sarnoff Research Center
- Digital Equipment Corporation
- Englehard Corporation
- Enterprise Integration Technologies
- Extrude Hone
- Factorial Systems, Inc.
- Ford Motor Company

- General Motors Technical Center
  General Electric
- General Dynamics
- Georgia Institute of Technology
- Giddings & Lewis, Inc.
- Grumman Aircraft Systems/Product Operations
- Hewlett Packard Company
- Honeywell Corp.
- Howmet Corporation
- Hughes
- Hughes Aircraft
- Institute for Applied Composites Technology
- Johnson & Johnson
- Lanxide Corp.
- Litton-Airtron
- Lockheed Missiles & Space Company, Inc.
- Lockheed Corporation
- Loctite Corporation
- LTV Aircraft Products Group
- Martin Marietta Corporation
- Martin Marietta Energy Systems, Inc.
- Masco Machine, Incorporated
- Meridian Corporation
- Mechanical Technology Inc.
- Microelectronics & Computer Technology Corporation
- Moore Special Tool Co., Inc.
- National Steel & Shipbuilding Co.
- Pennsylvania State University
- Protein Technologies International
- Purdue University
- S.E. Huffman, Corp.
- Sandia National Laboratories
- Sematech
- Sherwin-Williams Company
- Society of Manufacturing Engineers
- SofTech, Inc.
- South Carolina Research Authority
- Strategic Insight
- Sverdrop Technology
- Teledyne Brown Engineering
- Ten X Technology, Inc.
- Texas Instruments
- Textron Lycoming
- Timken Company
- United Technologies
- University of Miami/Department of Industrial Engineering
- Vindicator
- Xerox Corporation
- Xerox Advanced Information Technology

Additional copies of Volume 1 may be obtained by contacting the 21st Century Manufacturing Strategy Project office at the Iacocca Institute, Mohler Lab 200, Bethlehem, Pennsylvania 18015. Telephone (215) 758-4086. Fax (215) 694-0542.

Volume 2 is a companion volume which explains in more detail the infrastructure necessary for the transition to agile manufacturing. Volume 2 may be obtained by contacting the above address.