"COMPUTER AIDED MANUFACTURING:
A BREAKTHROUGH IN PRODUCTIVITY?"

by

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COMPUTER AIDED MANUFACTURING: A BREAKTHROUGH IN PRODUCTIVITY?\textsuperscript{1}

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Abstract

A Third Industrial Revolution is underway in manufacturing. As products become more complex, quality control becomes more difficult, and customers grow more demanding and diverse, mass production of standardized products is increasingly unsatisfactory. In responding to this challenge managers of manufacturing firms have been forced to face several critical questions and some difficult strategic choices. How must the firm change internally to compete successfully in the future? What technologies must be mastered and adopted "in house" and what can safely be contracted out? Is there an important distinction to be made between "human-centered" and "machine-centered" approaches? If so, which offers the best long term prospects? These managerial challenges have been compounded by the integration of the world economy. This paper presents some major results of a four-year study recently completed at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. The study concluded that Computer Integrated Manufacturing (CIM) is potentially a breakthrough of the "complexity-reliability-variety" barrier.

Hypotheses

The IIASA technology assessment of computer integrated manufacturing (CIM) began with seven linked hypotheses. We summarize these hypotheses briefly:

(i) \textit{Enabling Technologies: the "Supply Side".} Extraordinarily rapid improvements in telecommunications, micro-electronics and computers have created new possibilities for manufacturing that simply did not exist before. The rate of technological progress is not only high - one or more orders of magnitude per decade - but there are indications of acceleration since 1980 (\textit{Figures 1,2,3}). (See Technology section below). Manufacturing is the beneficiary, not the creator, of these forces. However, the impact of these technologies on manufacturing, primarily through their application to programmable automation, has been profound and far reaching. The existing and emerging capabilities of electronics are a fact of life — an unavoidable aspect of the environment. Business leaders must adapt to this fact.

(ii) **Changes in Markets, Consumers, Competition and Time.** Since World War II, international barriers to trade have been steadily reduced, while transportation and communications improved significantly. The resulting economic integration, and the emergence of Japan and the other export-oriented "Asian Tigers" as major manufacturers, has increased competition dramatically in American and European markets. Despite substantial barriers to entry, the number of automobile firms capable of competing on equal terms internationally jumped from perhaps 5 or 6 in the early 1950s to 13 or 14 in the early 1980s, and to perhaps 20 today, despite continuing pressures toward consolidation. In the U.S., imports jumped from 6% of the auto market in 1965 to 30% in 1990. No country in the EEC imports less than 30% of its total GNP.

![Figure 1. Development of Memory & Microchips](image1)

*Source: author, [adapted from Bursky 1983]*

![Figure 2. Inventions in Telecommunications](image2)

*Source: [Martin 1971]*
During the same time period, markets for many consumer goods have approached saturation. By the end of the 1970s one of every two people in the U.S. had an automobile, and 99% of American households had TV sets, refrigerators, radios and electric irons [Piore & Sabel 1984, p. 184]. Steady increases in disposable income were matched by the information revolution. Demanding, more affluent, better educated customers demonstrate ever-diminishing brand loyalty. There is an increasing willingness to discern quality from appearance. "Made In America" has long since lost its almost religious significance in the U.S. Volvo is no longer the locomotive of the Swedish psyche. Regional differences are hardly restricted to the U.S. In fact, they are undoubtedly more pronounced in Europe. Despite fear of the spread of U.S. culture (McDonald's, Coca Cola, Kleenex, Gillette razors, blue jeans and Walt Disney are clearly part of world-wide culture) there is no indication that regional markets are losing their identity. In fact, from relatively homogeneous markets with huge unspent demand, the world has been transformed into a collection of distinct market niches.

Merchandisers and distributors around the world have recognized the imperative to tailor products to these fragmented regions and market niches. In the U.S. producers must now reckon with "Yuppies", "DINKS", and (increasingly) with the affluent elderly. The world-wide auto industry saw 120 new models introduced between 1983 and 1988, as sales of individual models dropped. [Clark et al 1987, pp 3-5] Correct targeting of an unexploited market niche can mean substantial profits for the fortunate manufacturer — witness the Mazda Miata. The situation is no different for consumer electronics. Phillips, which produced about 100 different color TV models in 1972, put 500 on the market in 1988. It produced 10 types of CD players in 1982, but 150 in 1988.[? 1977, p. 77] There are 3,000 different models of Seiko watches, and over 55,000 models of
the IBM "Selectric" typewriter. The National Bicycle Company (Japan) now offers 19 models in 199 different color combinations with 6 different calligraphies, or a total of 11,231,862 variations. Sears Roebuck stores — and most large supermarkets — now have more than 50,000 items in stock.

Needless to say, the rate of change of product design has accelerated in lockstep, as product development has become the focal point of competition, for design directly affects product cost and reliability. [Clark & Fujimoto 1989 p.1] Product features, performance and reliability, have become at least as important as style and price in the marketplace. [Womack et al 1990] The desire for choice and variety of products which must be offered by each major competitor is a fact of life and permeates modern business.

Under the old regime of mass production, changes in the production process using single purpose machinery were so expensive that a new automobile model with major design changes was introduced only every 15 to 20 years. For manufactured products in general, the life cycle of products varied from five to as many as 13 years. Philips, Sony and Matsushita now have reduced the cycle for audio/visual products to one year, in some cases even less. Toyota and Honda can bring new auto models to market in two to three years. Production cycles (the time it takes to actually make an item from receipt of order) also are shrinking steadily. Motorola reportedly has cut the time it takes to build and ship an electronic pager from three weeks to two hours.

The rate at which a firm can develop and incorporate product innovations has become a dominant competitive factor. "Competitiveness in product innovation is more and more based not on achieving technological breakthroughs, but on the ability to provide model-specific features and the ability to compress the development cycles for new products. Such competitiveness depends on continual improvements in product development cost and reduced development leadtimes" [Imai 1990]. One study estimated that each day of delay in introducing a $10,000 auto to market would cost a firm one million dollars [Clark 1989]. To remain viable in world markets, firms must be able to differentiate their product lines from the beginning, yet deliver high quality at competitive prices, and remain flexible enough to increase or decrease volume sharply to meet demand fluctuations. A paradigm for manufacturers in the age of mass production might have been: "the most value for the lowest cost". Sharpened competition and the accelerated pace of technical product innovation dictate that firms of the 90's must rephrase this to: "the most value for the lowest cost in the least amount of time".

(iii) Complexity. Demand for new product features, the rate of increase in product innovation, and increased competition also have brought increased product complexity and corresponding escalations in manufacturing complexity. What was simple enough to be comprehended by a single individual in the days of cottage industry has now reached a stage of complexity that is almost unimaginable. The number of parts involved in a typical manufactured item has increased many fold (see Figure 4). The computer chip is now found in every product from refrigerators to cars; complex, computer controlled systems like anti-lock braking are commonplace. Xerox's top of the line photocopier has 30 microprocessors linked by local area networks which
monitor operations, and make adjustments for wear and tear [Brown 1991].

Production runs also have increased dramatically over the same time period. At the beginning of the 19th century a few thousand units produced over a period of years was long (e.g. Eli Whitney’s famous 1799 contract to manufacture 10,000 muskets for the U.S. army). Sixteen million ‘Model T’ Fords were made (1908-1926). Some standard items today — for example, bicycle parts and connectors — are manufactured in the millions of units per year.

(iv) Product vs Process Innovation. In the past twenty years we have seen ample evidence in America’s trade deficits that leadership in product innovation cannot guarantee success in the market. U.S. scientific genius and its once-proud manufacturing establishment gave the world television and the video recorder; today only one U.S.-owned firm produces TV sets in the U.S. — none produces VCRs. The ability to take state-of-the-art technology from the laboratory to the market place in a defect-free, pleasing package, depends on manufacturing process knowhow every bit as much as it does on design and marketing. Manufacturing engineering in the U.S., long relegated to second class status by engineering and business schools alike, is in the resurgence, but the loss of market share by our auto industry demonstrates how far we still have to go.

(v) Flexibility vs. Standardization. In the past, efforts to minimize production costs led to adoption of extreme standardization to facilitate ‘hard’ mechanization and extreme division of labor and hierarchical management structures (see Taylorism below). Mass production was the logical extreme application of economies of scale in manufacturing.
The impact of changes in technology and the market place on mass production has been traumatic, to say the least. Manufacturers increasingly are coming face to face with the Abernathy dilemma (or "productivity paradox"): the need to cut costs, by maximizing standardization and specialization using fixed capital, directly conflicts with the need to introduce new and improved products more and more rapidly (see Figure 5). The U.S. auto industry’s formerly dominant strategy of gradual, "managed" innovation and "planned obsolescence" itself has been rendered obsolete. Standardized products, differentiated primarily by style — the strategy introduced by GM — are increasingly difficult to sell, even with the advanced marketing techniques developed in the U.S. Put another way, large fixed investments in dedicated ‘hard’ automation are also a barrier to change to the extent that the fixed capital is inflexible and not easily convertible to manufacture a new or improved version of the product. Economies of scope, which we might define as increased flexibility of capital or capital-sharing, appear to offer a way out of this dilemma.

Flexibility implies the ability to produce a number of variants of the basic product, including new designs and "customized" revisions. In general terms the flexible factory is one whose cost structure is insensitive to variations in volume and product configuration. Batch sizes as small as one can be incorporated, and production can be altered to fit new or different products with minimal cost and time. Needless to say, the goal is to increase flexibility without increasing capital costs or sacrificing product quality.

Strategies (or means) of increasing flexibility are not limited to the use of programmable automation in place of fixed automation. There are significant organizational
considerations, as well as financial and logistic factors. We will touch on these matters briefly below.

(vi) "To Err is Human". The marketplace is increasingly unforgiving of errors and defects. Mounting product complexity also renders defective designs, components or assemblies increasingly intolerable. In a manufacturing process involving humans, "on line" errors result in defects, and, marvelous though they have proven to be, Japanese zero defect management simply cannot eliminate human error. Products and manufacturing processes have changed in the past two centuries, but humans remain essentially the same. The tendency to make mistakes at repetitive tasks is in-built. The Department of Defense, for instance, has found that the very best programmers can achieve no fewer than around 15 percent errors when entering code. Computers are inherently more reliable, as well as faster than humans at data processing tasks such as bookkeeping, and are much faster. Thus, computers, suitably debugged, can be uniquely helpful to humans in managing complex situations. Reduction of human error has become a major driving force of CIM. Technologies in existence now can achieve tolerances and accuracy far beyond the capability of human hands in machining parts, and can achieve direct transfer of digital design to machine tool programs untouched by human hands. Thus, increasing complexity in the product world induces increased utilization of computers.

Figure 6. Market Growth Driven by Scale Economies

Source: author

(vi) Economies of Scale vs Economies of Scope. For most of this century mass production was the driving force of economic growth. As charted in Figure 6, economies of scale (via product standardization and division of labor) made possible reductions in the unit cost of manufactured goods. Reduced prices relative to non-manufactured items led to
even further increases in demand, just as did increased payrolls for factory workers. Increased demand led to even larger scale production, more investment led to higher productivity, which lowered unit costs, and so on in a virtuous cycle.

Recognition of unsuspected regularities suggesting new approaches to systematization and better models

Availability of better operating data

Increased program-mability of machines

Shorter runs: "parts on demand"

Lower costs (See Figure 3.)

CIM: Increased integration of functions and control

Higher quality and greater flexibility

Increased responsiveness to customer needs and wants

Increased demand for customization

Figure 7. Market Growth Driven by Scope Economies
Source: author

We suggest that, as demand for variety in products increases and logical limits for economies of scale are reduced, economies of scope will become the new "paradigm for economic growth". This notion is sketched schematically in Figure 7. We believe that increasing flexibility progressively will reduce the cost differential between customized and standardized products. In order to decrease this differential, and to compete in a world of constantly shrinking product life cycles, firms will be obliged to invest in flexible capital. Investment in the new process technologies which constitute CIM and in modern management practices along Japanese lines, in turn appears to be leading to a monumental leap forward in both labor and capital productivity which could fuel the next growth cycle.

As always, in economics, there is a fly in the ointment. It is still much too early to say whether total employment needed to run CIM will be sufficient to maintain the demand for manufactured products and keep the economic engine turning.

CIM: The Next (Last?) Industrial Revolution

To summarize, we believe that CIM is so fundamental in nature, so potent in its effects, and so all-encompassing in its applicability that it is nothing less than a third Industrial Revolution. We see the first Industrial Revolution (c.1770-1830) as the period of adoption of
steam power to replace water and horse power, as prime movers to drive newly developed metalworking machine tools. The second Industrial Revolution (1880-1910) was an extension of the first. Electricity made it possible for centralized prime movers to deliver power to decentralized users. Internal combustion engines made power truly mobile (and led to heavier-than-aircraft and the final displacement of horses).

In these simplified terms, the third Industrial Revolution (c.1980-?) is CIM, viz. the adoption of computer power in manufacturing. After decades of anticipation, computers and 'smart sensors' are finally beginning to substitute for human brains in the factory, as well as the office. This is at least true for simple repetitive tasks which do not require the active use of human intelligence, except to convert a flow of information from one form to another. Programmable machine tools (NC/CNC), computer-aided design (CAD) and computer-aided process planning (CAPP) all offer major advantages in labor savings and information management.

This technocentric picture omits, however, a key dimension of the manufacturing problem: the management of the production process. A more revealing characterization of industrial evolution would be that the preindustrial period of craft guilds and cottage industry was coming to an end in the late 18th century, hastened by the Napoleonic wars. The first stage of mechanized manufacturing could be called the 'English system'. It applied the new power-driven machines to the old methods of production, and added increased specialization and de-skilling of labor. A more revolutionary change was the next stage, known as the 'American system' (1850-1920), which was developed initially in the arms industry of New England and subsequently exported around the world. The American system emphasized product standardization and interchangeability of parts, even when achieved at the expense of accuracy and precision of fit.

The next phase (1920-1960) was the heyday of 'scientific management', developed and promoted by Frederick W. Taylor and adopted most enthusiastically by Henry Ford. This was, in some ways, the logical extension of the American System which emphasized mechanical integration (assembly lines, transfer lines), hierarchical structure, vertical integration, cost accounting and extreme division of labor into 'optimized' tasks. Although the fallacies in the assumption that task level optimization results in optimization at the firm level were recognized long ago by mathematicians (in the context of linear programming models) they were not understood by managers and management literature until much later (if in fact they have done so today). Organized labor (in the U.S. and U.K. especially) first attacked task level optimization as 'exploitative' and 'inhumane'. But the labor movement has long since adopted Taylorism to its own purposes — in the guise of detailed job specifications -- as an effective means of assuring job protection.

The next evolutionary step was Japanese-style 'lean production'. This era, dating from around 1970 can be characterized by the simultaneous introduction of several new management techniques. The most important were "just-in-time" delivery or JIT (a Toyota innovation), "total quality control" or TQC (an evolutionary development of Deming's statistical quality control techniques) and "synchronous engineering". As we will see below, Japanese management of the supply chain and the labor force was also a critical "new" ingredient. (Many will argue that the latter skills were present in the American system, but lost under the Taylor era; others will point out that JIT and TQC also originated in the U.S. Be that as it
may, these ideas were much more thoroughly exploited in Japan. Few can dispute the success of Japanese management techniques. "While Japan was perfecting manufacturing, U.S. business was honing financial management" [Horn 1990].

In our view, computer integration (CIM) is shorthand for functional integration, or 'putting it all together' with the help of computers [Merchant 1962]. Information on manufacturing processes and business organization spreads around the world with incredible rapidity today, with highly educated work forces ready and able to apply new ideas. Investment capital flows equally rapidly across international boundaries. Demanding consumers constantly seek better products with little regard for nationality and competition in the integrated international market place constantly reinforces pressures for change that might otherwise be ignored. The computer facilitates, in fact multiplies, the benefits of lean production. The ability to collect and interpret real time data about the manufacturing process, inventory, sales, purchases and so forth can take 'lean production' into a totally new dimension. Meanwhile, lean production provides the organizational context without which the application of computers is fraught with pitfalls. CIM can be regarded as the beginning of a new era, marking a sharp break with the four decades (1950's through 1980's) during which computers consistently increased the speed and accuracy of a host of immediate applications but, somehow, failed to produce measurable increases in overall industrial productivity.

The most important single facet of the third Industrial Revolution may not be remembered in terms of automation or applications of the computer at all. In coming to grips with Abernathy's 'productivity dilemma' CIM has made possible the ultimate reconciliation of mass production and craft production. Future historians may remember this as the era in which it became possible, at last, to make products directly to order (in batches as small as one), instead of producing items in large volumes and attempting to sell what has been produced.

We can usefully summarize this historical view in terms of its application to a single manufacturing firm (Beretta, of Italy) that has manufactured one product - small arms - for 500 years, since the preindustrial era. Beretta's history since 1800 may be more or less typical of what has happened, and is happening, to other manufacturers; it is in any event a fascinating case study [Jaikumar 1989]. Beretta introduced Flexible Manufacturing Systems (FMS) in 1987. Shortly thereafter, it integrated Computer Assisted Design with CNC machines. As seen in Figure 8, gross output at Beretta has increased enormously through the years. The overall increase in productivity since the pre-machine period is close to 500-fold. Yet, absolute employment in manufacturing actually increased significantly until around 1950, when the first cuts occurred. Since then, direct employment has dropped by a factor of 10 (from 300 to 30), and the ratio of workers per machine has dropped from 13:1 to 3:1 (87%). The ratio of off-line workers to on-line workers has meanwhile grown steadily; off-line workers grew from 13% of the work force in 1867 to 67% today.

It is especially interesting that the early gains in productivity clearly owed a great deal to the design standardization that occurred between the English period and the American period. Recent gains in productivity at Beretta owe nothing to standardization, as product diversity has been growing. Productivity gains do, however, owe quite a bit to dramatic quality improvements. This is reflected by the drop in "rework" percentage: from 80% in 1800 and 50% in 1867, to the present very competitive level of 0.5%. Quality, in turn, is thanks largely
technology

For the purposes of this article, CIM is taken to comprise the integration of the whole range of programmable, computer-driven technologies that are making their appearance in the factories and offices of manufacturing firms. However, it is useful to identify three categories of manufacturing technology: enabling technologies, transitional technologies, and technologies central to CIM.

In the first category are telecommunications, micro-electronics and computers which developed independently of manufacturing technology per se. The second consists of technologies where micro-electronics and computers have been applied over the past thirty years, but mostly on a "stand-alone" basis. Examples include: Computer numerical machine tools (CNC's); Industrial Robots (programmable manipulators); Automated Guided Vehicles (AGV's) and Automated Storage and Retrieval Systems (ASRS). On the factory floor these technologies can sharply reduce "hands on" contact of workers with the product or workpiece (sometimes to zero). The role of humans as machine controllers, materials handlers, assemblers or inspectors is sharply reduced or eliminated, reducing error and defect rates by a startling degree.

The third category of computerized technologies introduces higher levels of integration. The major categories are Flexible Manufacturing Systems (FMS's) which consist of two or more CNC machines plus auxiliary robots, materials handling systems and ASRS, all controlled by
a single computer. Computer Assisted Process Planning (CAPP) is the acronym for systems that automatically control the routing and processing of workpieces. Materials Resource Planning (MRP) systems make computerized projections of future material needs. More important still are systems such as Computer-Aided Design (CAD) which directly convert digital design to machine code so that the design literally can be machined untouched by human hands. Such systems are often linked to Computer-Aided Manufacturing (CAM) systems, where a central mainframe computer coordinates the entire operation, including FMS systems, order processing and parts procurement. CAD/CAM is a major step toward full automation of flexible manufacturing.

CIM, then, can be defined as the integration of every aspect of the operations of a manufacturing firm: design, sales/orders, supply chain, parts management, manufacturing, inventory, final delivery, retailer/customer feedback, and administrative functions such as accounting and personnel.

There is strong evidence that the advance of the enabling technologies has actually accelerated since 1980. For instance, telecommunication channel capacity has increased faster than its historical rate due to the introduction of optical lasers and fibers. A similar acceleration can be seen in microelectronics and computers, due to the development of powerful microprocessors and the rapid rise of PC's and workstations. Computer prices, as a percent of other fixed capital, continue to decline rapidly. New applications cause change in machinery which is consistent with evidence of shorter product life cycles. Surveys in Japan show a reduction of 10.6% in machinery life cycles and 28.7% in the electronic machinery substitute, in just the three years 1981-84 [Mori 1989, Table 1].

Transitional technologies are both diffusing rapidly through manufacturing (see Figures 9 and 10) and increasing in sophistication and accuracy.

Today's major CIM software programs are moving rapidly toward incorporation of the entire operations of a factory/firm: business administration, accounting, bookkeeping, personnel, procurement, orders, sales and manufacturing operations. Access by every element in the firm to the shared central data base is a common goal, but one which no one firm seems yet to have attained. Communication between the central computer and the materials-handling computers controlling AGV's and CNC's is critical. Too often computer controls have grown up independently for various functions within companies; software may be totally incompatible even between machines on the same shop floor. Long-term strategic planning and shorter-term tactical planning can benefit enormously when based on the common data base integration demands.

From a management perspective, the technologies are extensions of traditional methods of human decision-making, but with far greater capacity to store, access and process information than previous generations of office automation. Surveys of management justifications for installing CIM tend most often to emphasize the need to increase flexibility, final quality and speed-to-market, rather than direct labor savings. However, from a technological perspective the change now underway is qualitative, not just quantitative. For the first time, computers handling different functions are being linked into networks which enable them to talk to each other without the need for human "transducers" at each interface.
Figure 9. NC/CNC Machine Tool Diffusion (% of total)
Source: author [adapted from Tani 1989]

Figure 10. Industrial Robot Diffusion
Source: author, [adapted from Tani 1991]

Flexibility
Flexibility is, in some ways, the heart of CIM. The concept is familiar, but in the manufacturing context it requires a somewhat more detailed discussion. ‘Flexible design’ is essential. Taylorist mass producers usually attempted to solve their design problem by finely dividing labor — by specializing designers. Development was usually linear and sequential. When designers completed their work, blueprints often were just "tossed over the fence" to manufacturing. Manufacturing engineers were supposed to figure out how to produce what the designers specified.

Lean production (c. 1970) introduced a major innovation: synchronous design, incorporating strong teams of designers encompassing both process and industrial engineering. Computer Aided Design (CAD) vastly increases the productivity of each designer, greatly facilitates the sharing of information and data (thus contributing to synchronicity), and generates a quantum step forward in flexibility. Product changes can be introduced rapidly on the factory floor, for they already have incorporated manufacturing parameters.

![Volume/Variety Trade-Off](source: author)

Manufacturing flexibility, focusing on variations in product configuration, timing and volume, usually occurs simultaneously with design flexibility. Volume flexibility (the ability to share capacity among products according to demand) is the first economic goal of FMS. An increase of production capacity through capital sharing can be the most important justification for a costly flexible manufacturing system, especially in small and medium size companies. Production flexibility (minimal barriers to a change in routing of workpieces, in tooling sequences, etc.) and product flexibility (the ability to vary the product within general parameters) are also critical. In general terms, the larger the part family the less total production capacity for a given capital cost (see Figure 11). Time consuming tool changes and setups will be necessary with each additional part, which decreases effective production.
time, and thus also total volume. FMS systems seek to achieve the highest cost/benefit ratio possible in the tradeoffs implicit in the various degrees of flexibility just outlined, varying with the complexity of the final product and the complexity of its parts.

FMS greatly increases the complexity of the manufacturing process and its vulnerability to interruption. Workpieces must move through the process in a meticulously regulated manner. Because at least 70% of materials used in a modern plant are "bought in", a subcontracting network capable of delivering high quality parts and components to exact time schedule is absolutely essential. Thus, supply flexibility becomes vital. In Japanese style lean production suppliers are located in close proximity to the final assembler and work intimately with the assembler. They may even share ownership, but at the very least they must eschew the adversarial type of relationships which came to characterize post-war mass production in America and much of Europe. The lean production method of organizing the supply network was responsible for an advantage of around $2,000 per car to Japanese automotive assemblers in 1989 [Womack et al 1991]. Distribution flexibility also is critical to assure delivery to the satisfaction of the customer or distributor as to place, time, size and mix. This requires flexibility in the administration of inventory, transport and order processing.

Flexible Manufacturing Systems - FMS

FMS itself is worthy of more detailed discussion, for it is in some sense the 'missing link' between programmable automation at the machine level and CIM. An FMS is inherently designed for batch production of a family of relatively similar parts. A technological historian of the future will probably think of FMS (if the term is still used) as a critical transitional stage. However, FMS is hardly an end in itself.

The first FMS's (for machining) were designed and built in the late 1960's and early 1970's. As often occurs with a highly touted new technology, costs were typically greater and benefits less than had been anticipated. There were many failures to meet unrealistic expectations. The biggest problem was human. FMS's are much more complex, with a far greater range of potential pathological behaviors, than the machines they replaced. Workers familiar with manually controlled machines or stand-alone CNC's were not able to operate - or troubleshoot - FMS's without non-trivial amounts of special training. Firms that failed to provide for this, especially in the U.S., often experienced serious difficulties. Most of the first generation systems are now obsolete. Beginning in the early 1980s, a much larger number of second-generation systems was installed, and performance has generally been more satisfactory. As of the beginning of 1990, more than 1200 FMS's had been built, world-wide [Tchijov 1991]. See Figure 12.

Impact of CIM on the Firm

The impact of CIM technology will not be visible until a fully integrated firm finally emerges. Even then "before and after" comparisons will be problematic, especially in view of the accounting problems left over from the age of Taylorism. However, there is a large number of anecdotal reports, already, documenting the results of applying different elements of the family of CIM technologies. It is, of course, quite difficult to isolate the effect of individual
technologies, as few firms actually install different systems serially. With these caveats in mind we offer the following observations:

In the design area, CAD has increased the output per draftsman in Europe between 200% and 6,000%, with an average gain somewhere in the region of 500% [Ebel & Ulrich 1987 p.353]. A survey of U.S. firms reveals that new product development time and costs went down by 50%, using "CIM technologies", and product lead time fell from 52 weeks to 18 weeks [Burt 1989]. Toyota reported recently that it had reduced design time by over 50% using CAD/CAM [Suri et al 1987]. Lockheed claimed a reduction of 81% [Gunn 1987a].

In recent years, documented labor cost reductions due to CIM technologies range from of 5% to 20%, on the low side, to 90% or even 95% in some instances. Introduction of FMS brought an average reduction in unit labor costs of 77% in 137 cases [Tchijov 1991]. A survey of 20 US FMS systems found the amount of labor required to perform the same work was reduced by more than 50%, while total product costs were reduced by as much as 75% [Hayes & Jaikumar 1988]. Caterpillar and Yamazaki have reported more than 90% labor savings in selected applications [Manufacturing Technology News 19??]. "CNC/CAM" saved an average of 63% in unit labor costs in the 35 U.S. cases surveyed by McAlinden in 1986 [McAlinden 1986, p.68]. Yet, at the same time, it must be acknowledged that a significant number of FMS' were failures, for one reason or another, most often because of inadequate planning or training of the personnel.

With regard to output/productivity, FMS gave an average increase in output of 490% in 61 cases reported by IIASA [Tchijov 1991]. McAlinden found output per man hour was up almost 140% after CNC/CAM was introduced. He also reported that robotics resulted in
productivity increases averaging almost 390% [op cit]. Takisawa Machine Tool reported in 1990 that its CIM plant using FMCs, AGVs, ASRS, fiber optic LANs, and point-of-production computer terminals increased output by 50% monthly (to 250 units) [Furukawa 1990].

![Figure 13. FMS Impact on Production Time](image)

Despite such startling results, it appears that other benefits of FMS/CIM may be more important. These include shorter throughput times, less floor space, less inventory stock, lower reject rates, and the ability to produce a variety of different parts with minimal set-up time (Figure 13). Indeed, reductions in throughput time are typically dramatic - often from weeks or months to days or hours. Gunn reported that large industrial firms achieved 200-300% increases in operating time of capital equipment using CIM [Gunn 1987 p.175]. Burt's study found production time dropped significantly, as set-up and processing times were reduced, and the number of rejects was down by 93% [Burt 1987]. Capital savings is significant when FMS has replaced a conventional transfer line. Conventional manufacturing systems use machine tools for their primary purpose (cutting) rather inefficiently (Figure 14). For typical U.S. job shops, only 6% of time is used for productive work, on average, rising to 22% for large-scale, high volume producers. As Figure 15 illustrates, average utilization rates of CNC's in FMS already approaches 40%, and may go as high as 60% by the end of the decade. Sharp increases in machine utilization also are recorded by small- or medium-batch producers. IIASA found FMS reduced the number of machines by an average of 78% for 84 cases, and work-in-progress by 77% for 64 cases [Tchijov 1991]. Required floor space drops sharply (50% seems to be the minimum), as multi-purpose, flexible CNCs replace traditional machines, and each machine is engaged in productive work much more often than traditional machines. An ECE survey of 20 locations in Europe found 70% fewer machine tools were needed for the same volume of production
Figure 14. Time Allocation; Various Scales of Production  
Source: author

Figure 15. The Impact of Computer Control on Machine Utilization  
Source: author

after FMS was introduced [UN 1986, p.124]. The possibility of approaching the utopian goal
of "zero defects" appears tantalizingly close. Both the reduction in inventory levels and in rejects (less space needed to correct errors) add to the savings in factory space.

As noted above, the benefits of shortening the time required for development and introduction of new products have only recently been clearly recognized in the management literature - mostly based on studies of lean production. Suffice it to say here that with cycles dropping under three years for new automobile models, and even under a year for some consumer electronics, only a few cycles are needed for a follower to become a leader. No single magical black box can speed up a firm's product cycle over night, but there is little doubt that CIM will become an essential tool in this regard.

CIM and the Legacy of Taylorism

CIM will have profound impact on management. Above all, it means the end of the Taylorist (or Fordist if you prefer) management philosophy. As Brooks and Maccoby have pointed out, Taylorism was based on a set of assumptions which already seemed quite obsolete, even before the advent of CIM [Brooks & Maccoby 1987]. A brief review of these assumptions (explicit and implicit) will prove enlightening:

Taylorist assumption #1: Management is a specialty. Managers must have absolute control over all aspects of work organization, including technology choice, investment and location. The most complex manufacturing enterprise can be organized and structured hierarchically into independent functions, tasks and sub-tasks. Boundaries between management levels and functions must be sharply differentiated.

It has long been known that hierarchical bureaucratic organizations (public or private), with rigid boundaries between functions and levels, impede information flow. Middle-level bureaucrats (and even top managers) often have more incentive for impeding the flow of information than for expediting it. Apart from this, the hierarchical structure is based on the implicit assumption that information flows only from the top down, not from the bottom up, yet significant elements of an organization's knowledge base reside even at the lowest level of the hierarchy

Taylorist assumption #2: The most efficient method of management is to subdivide labor according to task and to train workers to specialize in one, and only one, task or task element. "Labor", on the other hand, is generic and fungible; virtually any worker can be trained to do any non-managerial task. Tasks must be formally codified and reduced to "work rules" ("Rule of law, not men").

Taylor values workers at the lowest level of the hierarchy only because of their ability to perform "machine-like" tasks. This neglects the obvious empirical fact that many tasks require motor skills, knowledge and judgment of a fairly high order. In practice, the worker with long experience often knows much more about his particular job than his organizational superiors, even though he may not be able to articulate his knowledge in words.
Taylorist assumption #3: There exists one unique "best" way to accomplish each task, which can be discovered once-for-all by experimentation and analysis (time and motion studies). These studies can best be accomplished by trained specialists. This assumption falls without the additional assumption that product and production technology are static and stable.

It is obvious that the manufacturing environment is changing constantly (CIM is itself a fundamental change). The more dynamic the environment, the more likely decisions made by managers will be based on obsolete technical knowledge, and the less appropriate will be the hierarchical organization. Just as generals too often prepare to fight the last war using outdated strategies and tactics learned in military academies, top managers in manufacturing often are familiar only with the technologies they learned in their "business academies" or as young engineers. Even competent engineers, when long divorced from the shop floor by promotion to management, end up making critical decisions among alternate technology choices with far too little knowledge about the current state of the art. More often than not, in the American system, top decisions makers are marketing experts or lawyers with little or no technological knowledge who were more capable at climbing the corporate ladder than technical experts.

Taylorist assumption #4: The "one best way" of performing each task is independent of what is being produced or how it is being used. Thus, errors and defects are "cost-free" to the manufacturer, as there is no tradeoff between operating rate and error rate.

Corporate financial decisions rely far too heavily on an accounting methodology based on this obsolete assumption about production relationships. It is well-known that large American manufacturing firms have been obsessed with reducing direct labor costs, while neglecting opportunities for reducing overhead and other indirect costs, such as defect rates. The prevailing accounting methodology, developed in the 1920's, during the ascent of Taylorism, fails to give adequate weight to quality improvement and to reducing costs which add no value, such as inventory, inspection, rework, repair, warranty and so on. Only recently has this subject been addressed in depth by members of the accounting profession [e.g. Kaplan 1989]. Today all managers agree there is always some cost, varying according to circumstances. In practice, Taylorist mass manufacturing attempted to correct assembly errors at the end of the line, a costly and inefficient method which was one of the principal reasons for American competitive disadvantages versus lean production in the 1970s and 1980s.

In fact, there is a mountain of evidence from the ergonomics and industrial psychology literature on the tradeoff between the rate of performance of any task and the percentage of errors made [e.g. Miller 1978]. Generally speaking, the error rate increases non-linearly with the rate of information input. It is this relationship that determines the theoretical maximum rate of performance. The error rate of a human worker (or an inanimate information processing system) is non-zero even at very low input rates, but the rate rises sharply as the information processing capacity of the worker or system is approached. Reducing error rates is an integral part of CIM.

Taylorist assumption #5: As each task is independent of the others, the best result for the firm as a whole will be achieved by maximizing output of each task or of each unit of
labor. Thus, costs to the firm associated with interference or interaction between functions or tasks are assumed to be negligible or non-existent.

This dangerous misconception ignores the fundamental fact that manufacturing is a complex, interconnected system. In reality, it is much more accurate to assert that "everything depends on everything else". Every system must be analyzed holistically, as first emphasized by Harrington [Harrington 1984]. One key element of a holistic approach is the need to identify and eliminate bottlenecks in the flow of work in progress [Goldratt & Cox 1986], as in the philosophy of JIT inventory delivery used in lean production. In the future it will be increasingly necessary to identify and eliminate bottlenecks in information flows, as well as material flows.

HIM/Lean Production

Although the very essence of CIM has been the ability to reduce human error and cost (while enhancing labor productivity and reducing uncertainty), the example of Japanese-style lean production and practical experience have produced a totally new framework for CIM. The elements of lean production are as follows:

(1) Long, stable, interdependent relations with suppliers of parts and components (often through interlocking ownership);

(2) Flexible automation;

(3) Emphasis on zero defects (even more important than cost minimization);

(4) Just-in-Time parts delivery;

(5) Integrated product design and development (synchronous engineering);

(6) A well-trained, motivated, flexible, pro-active work force, operating without rigid work rules; and

(7) Diversification of decision making and a flattened hierarchical pyramid.

These factors, more than protection or government intervention, have been the key to the success of Japanese manufacturing. Moreover, they preceded the computerized integration which characterizes CIM technologies [Womack et al 1990].

Each of these elements is consistent with, or even facilitated by, CIM. Japanese firms, for example, typically integrate as many of the distinct manufacturing functions as possible in the design process, including the factory floor and engineers from suppliers of parts and components. CAD simplifies and accelerates this synchronous engineering process. Both JIT and FMS are highly fragile to interruptions in parts flow so firms have been moving rapidly toward enhancing their supply networks, even where the lean production example has not been emulated. Computer handling of inventory, sales orders, order projections, and even direct electronic ordering greatly facilitates management of this supply network.
The impact of the pro-active role of Japanese workers in the production process was long apparent to Western observers. However, movement in that direction has been slow and less than uniformly successful. This is only partly due to the managerial culture of Taylorism. It is also attributable to the role of organized labor in Europe and North America. (Japan has no industrial unions in the western sense, nor do Japanese labor contracts include detailed job descriptions.

Another factor is that mass production had led to the steady de-skilling, and spatial re-distribution of direct labor. This is a process that is difficult to reverse. Although CIM yields a substantial reduction in the amount of direct labor hours needed to produce a fixed number of products and increases the degree of management control, it also requires a substantial increase in the necessary skill level and initiative of workers on the factory floor. At the same time, it promotes less direct management control; it flattens the management pyramid and promotes horizontal dissemination of information. Workers who once might have managed a high-speed lathe now must be able to manage, even program, three or more CNCs; they may very well be authorized to make maintenance and procurement decisions on the factory floor.

Japanese manufacturers claim to consider the worker their most important fixed asset. They do vest far more authority in the line worker. They also demand far more in terms of process and even product innovation, from workers than is the case in the U.S. This is the quid pro quo for a "lifetime employment" guarantee. "Western firms emphasize technological solutions to increase productivity and reduce costs by eliminating labor which is considered an unstable variable during production. In Japan, manufacturing strategy is shaped by a humanistic culture that emphasizes loyalty and the role of the worker at the job site" [FMS Magazine 1988]. One Japanese auto assembler has documented over two million discrete improvements in the production process suggested and implemented by workers on the factory floor — without any special compensation [Cole 1991]. All of this has led one Toyota representative to say Toyota doesn’t use the term CIM because "the computer is only a tool that we use in our process, not really the heart of our system of manufacturing" (Personal communication).

European and Japanese firms fear that by overemphasizing the computer and its ability to replace skilled labor they may lose the interpretive and cognitive skills which cannot in the foreseeable future be replaced by a computer (at least until Artificial Intelligence of near-human capability is a practical reality). Loss of these skills to technological developments in CIM might outweigh other possible gains. "The important advances in quality at assembly nowadays are coming not from the architecture of chips so much as from the organization of people, from people-integrated manufacturing, not from computer-integrated manufacturing." [Kumpe & Baldwin 1988].

In response to these considerations, many Japanese (and European) firms are moving toward what they call HIM — Human Integrated Manufacturing. In contrast to CIM, HIM recognizes that "the high level of interdependence and integration among FMS components and the demand for immediate response mandate an unusual degree of dependability in operators if the system is not to shut down". HIM emphasizes the interaction between FMS technology and people - flexible people - who plan and operate it. Broad skill mixes, previous experience with start-ups, cross-training, cross-functional cooperation, job rotation, team-building, and
provisions for continuing experimentation and adaptation all are seen as necessary if FMS is to succeed.

The contrast with U.S. firms, from this perspective, is stark. U.S. managers, with few exceptions, remain wedded to the Taylorist paradigm. U.S. firms are excessively hierarchical, excessively compartmented, and excessively influenced by an accounting mentality supported by an obsolete accounting methodology. They treat blue-collar employees as if they were interchangeable parts in a machine, rather than important ‘human resources’. Workers on the factory floor don’t really communicate with supervisors and managers don’t know as much as they should about how the manufacturing system actually works. "It is increasingly evident that the competitive advantage of the Japanese lies not in greater adoption of automation or in cultural differences, but simply in the way the work force is managed, particularly the way the talents of the entire work force, from top to bottom, are involved in a holistic company strategy" [Brooks & Maccoby 1987].

CIM Diffusion

A key question we must ask is: "how fast are CIM technologies spreading in manufacturing?" The adoption of CIM involves comparison, evaluation and explicit choice among alternate strategies or systems at several levels of abstraction. For example, a factory manager may chose among robot vendors only after making prior choices about robot architecture, drive systems and even between robots and human workers in particular applications. A large firm must also choose computer systems which will maximize inter-firm communication without inhibiting plant flexibility. As noted above, the desirable degree of flexibility is very much a function of the final product, the complexity of that product (before and after CAD), the type and complexity of machining necessary, and the volume of production. Desired flexibility in turn will affect the choice among alternate technologies. As always, the final decision mechanism is the calculus of costs versus benefits.

There are three problems with measuring the CIM adoption rate, and thus projecting future diffusion. First, most diffusion models assume that the "product" remains unchanged after diffusion starts. In the real world, CIM evokes active, conscious feedback between the primary technology developer and the customer/user; CIM software typically is revised many times by adopters as they run up the learning curve. Thus, classic S-curve studies of diffusion have difficulty estimating inflection points.

Second, CIM is a holistic concept involving many choices between alternate solutions to the manufacturing problem, solutions which are seen differently by almost every practitioner. There are few, if any, cases where a complete CIM system exists, despite reports about such "factories of the future" as Saturn, Yamazaki’s machine tool factory, NEC’s famous Orange Line, or Hitachi’s electronics plant. Because of these definitional problems we inevitably end up measuring the diffusion of the various CIM elements, instead of CIM itself. Even in the case of components the data are mushy, as definitions still vary. FMS’s, for example, may turn out to be simpler FMCs on closer examination.

Third, studies of CIM technology to date have told us simply whether or not a particular technology, e.g. CNC, is in use by a firm or plant. But the degree to which total manufactur-
ing capacity has been converted to the new technology remains uncertain. Finally, because diffusion studies focus primarily on metal cutting they rarely can incorporate the degree to which businesses have adopted other forms of CIM. Even firms which find flexible automation of manufacturing to be uneconomical will benefit from JIT, from automation of their accounting and sales figures, and so on. The degree of computerization in banking and insurance is a perfect example, though well beyond the boundaries of this article. In the absence of reliable direct data on CIM, we have focussed here on the integrating technologies which are key to more complete integration.

![Figure 16. CAD Diffusion](source: author, [adapted from Astebro 1991])

*Figure 16* depicts the diffusion of CAD, one of the few CIM technologies in which the U.S. still has a considerable lead over the rest of the world [Astebro 1991].

Of the 100,000 manufacturing units in the United States, more than 40% have one or more elements of CIM technology, according to the 1988 U.S. census survey of manufacturing [USCensus 1989]. The IIASA study identified 107 plants in the US (mostly large) where all or nearly all the elements of CIM are present and integration is quite advanced. Typically these firms are in the electronics, automotive, aerospace, heavy equipment, appliances or agricultural machinery industries. Raju surveyed 37 of those plants, and found FMS was in use in over 75%. 60% had integrated FMS with CAD to some degree (the degree varied widely). The integration of robots with CAD, CNC and other process machines was fairly high, especially in the electronics industry. Integration at the lowest level (machine groups at the shop floor) was behind that at higher levels (integrating data between distinct functional areas of firms, or integrating separate units of large multi-plant, multi-product corporations). In particular, it is still uncommon for CAD systems to drive CAPP or FMS directly. The diffusion of CNCs in the major countries is surprisingly similar (contrary to some press
stories). Japan is only slightly ahead in terms of overall use of this technology, but leads by about four years in the adoption of robots.

Tchijov [Ayres & Haywood 1991], attempted to forecast FMS diffusion based on IIASA’s World FMS data base. He estimated FMS systems would grow by 11% per year in the 1990s, then slow to around 3.6%. The world FMS population, about 1,220 units in 1990, would thus reach 3,500 units by the year 2000, and 5,000 units by 2010. For the U.S. the totals are 230, 660 and 1,060, respectively; for Japan they are 370, 880 and 1,200.

We believe these figures do not really reflect likely diffusion rates. These forecasts cannot encompass, for example, the emergence of new technologies, such as CNC lasers or plasma cutters. There is also an intense competition underway among purveyors of CIM as an independent software concept or idea. Firms as diverse as Nissan Steel, Digital Equipment, IBM, NEC, Hewlett-Packard, Battelle Institute and Price Waterhouse offer "complete" CIM packages. The Japanese have proposed to the U.S. and EC a billion dollar joint effort to identify the Intelligent Manufacturing Systems of tomorrow.

We believe that once the Pandora’s box of computer controls has been opened, as it has been already for more than 40% of U.S. manufacturing corporations, the diffusion curve will cease to resemble Tchijov’s S-curve. The rate of change in product technology, the escalating rate of growth in computing power, and ever-more rapid information transmission around the world all will contribute to a rapid and prolonged increase in the use of all CIM technologies. This, in turn, will move manufacturing very rapidly along toward the goal of CIM. We would be very surprised if 25 percent of U.S. manufacturing firms are not claiming to utilize CIM by the end of the present century. On the other hand, the diffusion process will not be completed, we suspect, much before the middle of the next century.

Process Industries

We have concentrated on discrete parts manufacturing, yet we should touch lightly on CIM developments in the process side, as well. The discrete parts industry involves individual parts, processed in discrete or batch lot operations, and assembled into discrete products. The process industries such as petroleum refining and chemicals (more precisely the fluid process or continuous process industries), make products which flow continuously through the manufacturing process. From the beginning, fluid processes demanded production devices which could measure the basic parameters of flow, pressure, level and temperature in real time. Moreover, competitive advantage in the production of large volumes of a commodity tended to go to the producer with the most efficient process, as opposed to the emphasis on product in discrete parts manufacturing. As a result, automation proceeded much more rapidly in process than in discrete manufacturing.

During the period between 1940 and 1960, plant controls in the process industries were steadily centralized in areas more and more remote from operating areas. Control centers became larger and more complex, as electronic controllers in the 1950s allowed for longer transmission distances and analog-electronic controls replaced mechanical-pneumatic. Supervisory digital control computers and digital direct control computers began to be introduced in process control systems in the early 1960s and greatly facilitated feedback
controls. (Concepts of computer control were actually developed using early analog computers, but proved so complex they had to await the arrival of digital memory, in practice). The lower cost and high reliability of microprocessors after 1980 led to their use in most process controllers and measurement devices, allowing the distribution of many functions which previously were handled only in higher-level computers. Supervisory and plant management control are still highly centralized, with increased graphic, simulation and diagnostic aids. But process control systems now generally are via open distributed architecture using digital LAN's. Today the accepted wisdom is that the process industries are well ahead of discrete manufacturing in actual plant operations, but trail in business applications. [Bernard 1989]

**Economic Implications of CIM**

We have used the term 'revolution' rather freely in this article because the impact of CIM marks a watershed in manufacturing, and a major upheaval in economic conditions. One economic consequence noted already is that economies of scale will give way to economies of scope in importance. Another is that labor cost is declining sharply as a competitive factor. Many observers project that direct labor costs will be less than five or even three percent of total costs in factories of the 21st century [Gunn 1987a]. CIM technologies already are available "off the shelf", and their adoptability has been proven by U.S. auto firms operating in less developed countries such as Mexico. This implies a rapid dissemination globally of CIM manufacturing techniques, and a declining advantage in regions currently specializing in manufacturing for export.

This, in turn, implies less long-distance trade of many manufactured goods. Manufacturers also will have less incentive to produce in low-wage areas for export to their home countries; instead, they will have more incentive to invest directly in productive capacity in the market to which they expect to sell. Direct investment will replace a sizable portion of exports. Large items such as jet airliners, and goods which require large direct labor input or which are amenable to fixed, inflexible automation are the exception.

As noted at the outset, product life cycles are contracting. Thus, competitive advantage is increasingly based on responsiveness to the market, i.e. getting new products out faster [Stalk & Hout 1990]. Short turnaround times mean that imitation is progressively easier. Rapid dissemination of basic scientific discoveries dictates that product innovation will provide ever more fleeting advantage. As a result, patents on products are less effective, hence less important. Only manufacturing competence (the ability to manage production, as exemplified by lean production) itself offers real protection - because it is much harder to imitate than are products.

The growth industry of the future is clearly software, which is also the core of CIM. Software eventually will incorporate much of the 'knowledge base' of every manufacturing (or other) business. Yet, the software architecture must be flexible enough to accommodate growth and change. Designing the basic system is a formidable task. This will be a major challenge, and a wrenching discontinuity, given the extreme difficulties and risks (for many businesses) in farming out the task to outside vendors. Many top managers fail to meet the challenge, either because they try to delegate the problem to outside network managers or to low-level in-house
functionaries who try to program existing procedures into computers without fully understanding them.

![Figure 17. Software as a Fraction of Total Capital Investment](source: author)

An increasing percentage of so-called "fixed" capital consists of specialized software. *Figure 17* depicts software costs as a fraction of total capital costs. As the span-of-control by computers extends from the machine level to the factory (or firm) level, the software requirement will grow disproportionately. While the actual numbers for software costs are uncertain (because no government statistical agency has yet thought to try to measure them), the rising trend is clear. Capital investment in software is unquestionably being under counted, insofar as many firms are forced by existing accounting rules to treat in-house software development as an expense, rather than as an investment. A good deal of work will be required from future national accounts statisticians and economists to identify the proper role and importance of software. Policy makers arguing for better-directed public education should take notice.

The decline of direct labor costs comes from a substitution of flexible machines for labor. This translates into higher labor productivity (although labor productivity is becoming less and less meaningful as a measure in the face of the competitive need for flexibility). Employment in manufacturing appears likely to decline steadily as a percent of total employment, notwithstanding contrary suggestions [e.g. Leontief & Duchin 1986]. Jobs created in areas such as software development will be unlikely to offset labor saving effects of individual technologies such as CAD and CNC. In fact, even software development is yielding to "automation" as new computerized software production techniques evolve.
One unresolved question deserving further study is whether CIM offers an alternative mechanism to drive growth [Ayres & Zuscovitch 1990]. Product quality is increasing rapidly. Consumers probably will benefit from lower prices for identical products. Prices are likely to increase for products like autos, to pay for new features. But the classical growth mechanism driven by economies of scale (mentioned earlier) appears to be out of date, if not defunct. The optimistic view of CIM as growth mechanism would focus on shorter product life cycles and the speed-up in innovative activity as a primary factor impetus for continued growth. The question remains: can an accelerated innovation rate in terms of new product features offset the disappearance of economies of scale?

Economists must also focus on the importance of capital productivity, especially resulting from steadily declining inventories. Traditionally, the pendulum swing of stock building has provided a substantial part of the variation in business cycles. Forecasters who have invested heavily in models forecasting inventory fluctuation, or who use inventory fluctuation as key indicators, must take notice of the major structural shift rapidly taking place. Factories capable of operating a second shift with only a minor increase in employment, and who may operate a third shift almost totally unmanned, also will be far less likely to lay off workers during a downturn in the business cycle, and will need to hire far fewer during upturns.

Implications of CIM for Less Developed Countries (LDC'S)

Finally, the situation of LDCs deserves special consideration. We don’t pretend to have all the answers, only some of the questions. But there are disturbing implications in the trends we have identified. One is that low cost labor is unlikely to provide a platform for export-led growth (as it did for the "Asian tigers"). Yet, cheap labor is the only advantage offered by most LDCs. Moreover, the increasing demand for product quality works against labor-intensive methods, especially where productivity is correspondingly low. By this line or argument, CIM has to be viewed as a major threat to the growth prospects of LDCs, at least insofar as they hope to export manufactured goods to the industrialized world.

Indeed, it is no less a threat to the former socialist ‘East Bloc’ countries. On the other hand, if CIM can be ‘home grown’, or purchased off the shelf and adapted, it offers a possible way of supplying local needs (including capital goods) without importing them from far away, at high cost. Countries with large internal markets (India, China, Brazil, Indonesia) can hope to attract foreign investors who will bring CIM technology with them. Smaller nations may hope to increase the size of their ‘internal’ markets by forming regional common markets.

Some nations, primarily those relatively close to manufacturing centers, may still benefit by specializing in those intermediate goods still requiring a large direct labor content, such as assembly of bicycles, TV’s or PC’s. As an engine of growth, however, even investment in "offshore" production facilities in the few remaining labor-intensive items will be fraught with danger. The manufacturing process itself is now changing so rapidly that it will be essentially impossible to be sure of picking long-term winners immune from competition from CIM. Moreover, the demands of JIT for steady, high quality, on-time delivery and the fragility of the FMS-type operation to interruption in the flow of parts and components will force assemblers into ever-tighter geographic concentrations with short transport links. This discourages long-term commitments to depend on LDC sources.
A higher rate of technological innovation in the "north" could be either good news or bad news for the LDCs, depending on whether the resulting technological improvements can be implemented for their benefit [Columbo 1990]. The fact that CIM technologies require far fewer direct labor hours per unit of output may mean that manufacturing industry no longer can be considered as the major engine of employment growth in LDCs. On the other hand, an outpouring of higher quality, cheaper products in LDCs should create a positive trend in terms of increased standard of living, and increased aggregate demand. The "old" paradigm of economic growth based on economies of scale may still be valid in the LDC's for a long time to come. That conclusion begs for in-depth study.

References


[Womack 1989]


Figure 1. Development of Memory & Microchips
Source: author, [adapted from Bursky 1983]
1 voice channel is taken as equivalent to 2000 bps in plotting these points. Numbers in parentheses give voice channels carried.

- Coaxial cable & microwave highways (32000)
- Coaxial cable links (600)
- Microwave links (1800)
- Carrier telephony first used (12 per wire pair)
- Telephone lines first constructed
- Baudot multiplex telegraph (16 telegraph machines per line)
- Printing telegraph systems
- Early telegraphy, Morse code dots & dashes
- Oscillating needle telegraph experiments
- Lasers
- Planned helical waveguides (100,000 or equivalent)

**Figure 2. Inventions in Telecommunications**

Source: [Martin 1971]
Figures for CIM: A Breakthrough in Productivity?  
R.U. Ayres & D. Butcher  
November 17, 1992

Figure 3. Efficiency of Computing Architecture  
Source: author, [adapted from Bursky 1988]
Figure 4. Complexity Trends

Source: author
Figure 5. The Productivity Dilemma
Source: author
Price reduction

Market growth

Larger scale production

Increasing experience

Cost reduction per unit

Production standardization

Figure 6. Market Growth Driven by Scale Economies
Source: author
Recognition of unsuspected regularities suggesting new approaches to systematization and better models

Availability of better operating data

Increased programmability of machines

CIM: Increased integration of functions and control

Lower costs
(See Figure 3.)

Higher quality and greater flexibility

Increased responsiveness to customer needs and wants

Increased demand for customization

Shorter runs:
"parts on demand"

Figure 7. Market Growth Driven by Scope Economies
Source: author
Figure 8. Six Epochs in Process Control
Source: author
Figure 9. NC/CNC Machine Tool Diffusion (% of total)
Source: author (adapted from Tani 1989)
Figure 10. Industrial Robot Diffusion
Source: author, [adapted from Tani 1991]
Figure 11. Volume/Variety Trade-Off
Source: author
Figure 12. Diffusion of Flexible Manufacturing Systems
Source: author, [adapted from Tchijov 1991]
Figure 13. FMS Impact on Production Time
Source: author
Figure 14. Time Allocation; Various Scales of Production
Source: author
Figure 15. The Impact of Computer Control on Machine Utilization

Source: author
Figure 16. CAD Diffusion
Source: author, [adapted from Astebro 1991]
Figure 17. Software as a Fraction of Total Capital Investment
Source: author