(1) FUTURE TRENDS IN FACTORY AUTOMATION
(2) TECHNOLOGY FORECASTS FOR CIM

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FOREWORD

These two papers form a natural package. Both appeared in earlier versions as IIASA Working Papers for the CIM Project. The second one also reflects a major thrust of the project, which culminated in the summer of 1989. (A second paper by J. Ranta reflecting on that effort will appear separately.)

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Future Trends in Factory Automation

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This paper is a review of contemporary manufacturing technology, from both a U.S. and world perspective. It emphasizes the historical background of the current trends toward computerized automation in terms of the increasing societal demands for performance, which in turn generates requirements for ever greater complexity and precision. This is the root of the "quality crisis." The author believes that the next industrial revolution will present a fundamental shift from the use of human workers as "micro" decision makers (machine controllers) in factors to the use of "smart sensors" for this purpose. The paper elaborates some of the more specific implications.

DISCRETE METAL PARTS MANUFACTURING TECHNOLOGY (c. 1975)

The choice of manufacturing technology at present is highly dependent on the scale of production. But some items, such as connectors, have long been standardized and mass produced in enormous numbers whereas other items, such as auto engine plants or space shuttles, are virtually custom made. The cost per unit of items made in large numbers can be as little as one-hundredth of the unit cost of the same item made individually. For example, the 600 distinct machining operations required for a V-8 cylinder block in 1975 cost around $25 in a mass production plant and only required 1 min. productive labor time. By contrast, the same 600 machining operations carried out by skilled machinists in a job shop would have required 600 min. of machinist labor and cost at least $2500 [1, 2]. One of the ironies of this situation is that the specialized machinery typically used in mass production, for example, the large transfer lines and multispindle drilling and boring machines, are themselves customized, one-of-a-kind investments.[1] If auto engine plants could be mass produced as auto engines are, the capital costs would drop by as much as 100-fold.

A more recent example is instructive: helical rotors for compressors, as first produced in Sweden by hand in the 1950s, required up to 200 machinist hours. By 1967 this had fallen to 6 h, by 1978 to 65 min. and in 1979 to 26 min. [3]. None of these advances utilized numerical control, which entered the picture subsequently.

[1]The design of an auto engine plant, capable of producing 120 units per hour for 20 years, requires about 60,000 engineering man-hours [2].

However, in our diverse economy it is natural that some items, especially durable goods, are needed in small numbers and seldom replaced, while others are needed in larger numbers. The distinction most commonly made is between batch and mass production. The value added of the U.S. manufacturing sector in 1977 was about equally divided between these two categories, as shown in Fig. 1. Batch manufacturing can be further divided into one-of-a-kind (piece) or very small batches and medium to large batches, as indicated in Fig. 2. Unit cost differences arise from several factors. In the first place, small volume production is inherently much more labor intensive than large volume production because fewer functions are automated. Table 1

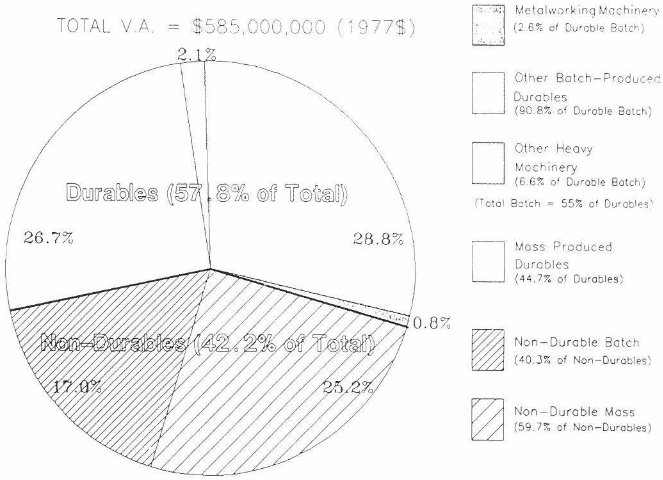

FIG. 1. Distribution of manufacturing value added (Source: Miller, 1983 [11])

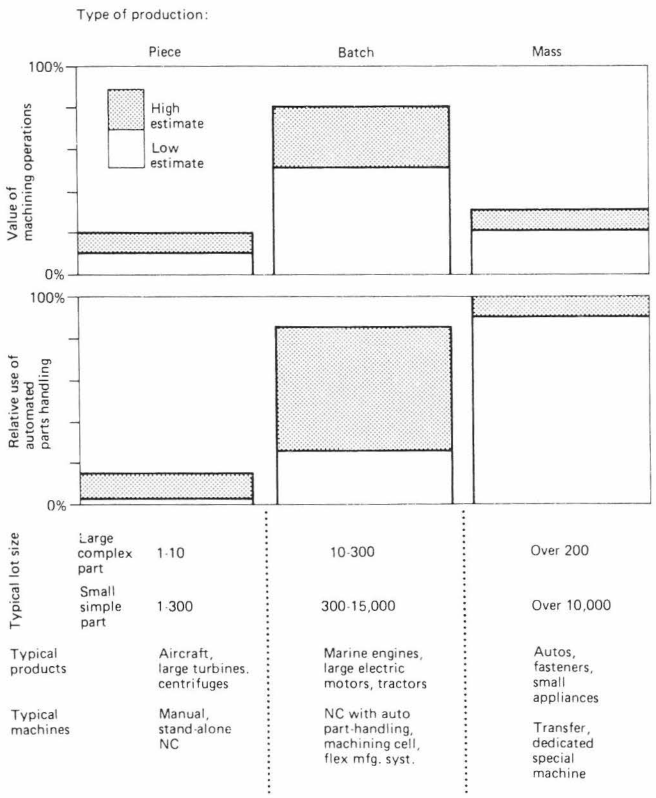

FIG. 2. Characteristics of metal product manufacturing (Source: *American Machinist*, 1980 [4])

shows the progressive elimination of manual operations by automated equipment of increasing degrees of sophistication.

Another reason for the big difference in unit cost between mass production and piece production in a job shop is that machines can be utilized much more efficiently in the former case. Differences in typical machine utilization patterns as a function of scale of production are shown in Fig. 3. It is noteworthy that in a typical job shop machines are only tended about 20% of the time and only 6% of the time is used for productive cutting. This contrasts to 22% productive cutting in a mass production facility [4].

Table 1. Comparison of manual manufacturing steps elimination by various degrees of automation (Source: General Accounting Office 1976: p. 38)

	Production Methods			
Step	*Conventional*	*Stand-alone NC*	*Machining center*	*FMS*
1. Move workpiece to machine	M	M	M	C
2. Load and affix workpiece on machine	M	M	M	C
3. Select and insert tool	M	M	C	C
4. Establish and set speeds	M	C	C	C
5. Control cutting	M	C	C	C
6. Sequence tools and motions	M	M	C	C
7. Unload part from machine	M	M	M	C

M = manual operation C = computer-controller operation

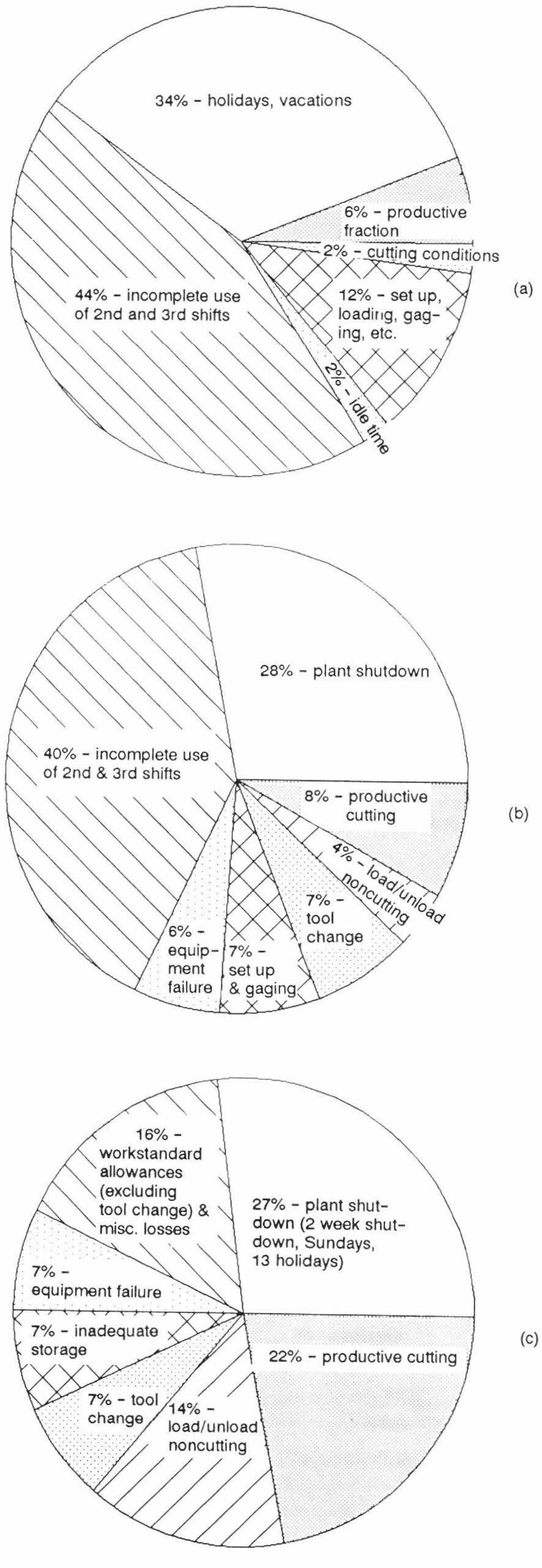

FIG. 3 (a) Low-volume manufacturing, (b) mid-volume manufacturing, (c) high-volume manufacturing (Adapted from: *American Machinist*, 1980 [4])

The key characteristic of mass production is that it achieves low unit cost by extreme specialization of equipment. For automobile engine or transmission production, the heart of the plant would consist of a set of giant multiple-spindle machines, generally with between 100 and 1000 tools, mainly drills, cutting simultaneously. The spindles are clustered in groups (or stations).

The mechanical requirements are exacting. Each of the spindles in each station must be permanently positioned very precisely with respect to all the others. All the spindles in each group must also be exactly synchronized, so that the resulting holes are not only parallel but also drilled to the exact same depth. Drill speeds must be precisely predetermined for the same reason. The necessary simultaneity can be achieved by mechanically linking all the spindles at each station, via elaborate gear trains, to a single drive shaft. Or, separate drive motors can be subject to a common controller. Workheads are either ON or OFF. Machines are designed to operate at a fixed speed over a fixed cycle that is optimum for the design application.

Large groups of machines (sections) are also synchronously linked together mechanically via indexing transfer lines. They are not individually controllable, hence not easily adaptable to other design specifications. If the product being manufactured becomes obsolete the custom-built manufacturing equipment is likely to be scrapped, since adaptation is difficult or impossible. This rigidity explains the otherwise puzzling fact that U.S. automobile manufacturers in the 1970s were not able to convert plants from eight-cylinder-engine production to six-cylinder-engines. For the same reason, a plant dedicated to making conventional transmissions and drive shafts for large rear-wheel-drive vehicles could not be converted to manufacturing transaxles for front-wheel-drive cars.

The economics of such special-purpose automation, as compared with other modes of manufacturing, is indicated schematically in Fig. 4. The curve represents the cost-minimizing choice as a function of scale of production. Evidently, fixed costs are very high but variable costs (mostly labor) can be minimized. Thus hard automation pays off when production volumes become large enough.

While the mechanization of parts manufacturing has not yet reached any physical limits, its contributions to gains in manufacturing productivity were diminishing by the 1970s. Even within the manufacturing arm of a big "systems integrator," logistics,[2] assembly, and quality control[3] now account for, by far, the biggest share of the real costs of manufacturing—quite apart from indirect costs of finance, marketing, personnel management, and the like. To reduce costs significantly—below present levels—a completely new technology of production permitting substitution of "smart sensors" for "hands-on" labor, and coordination of all activities by computer, seems to be needed. This will become increasingly manifest over the next two decades.

The long-range imperative, of course, is to design the human worker out of the production system. Thanks to

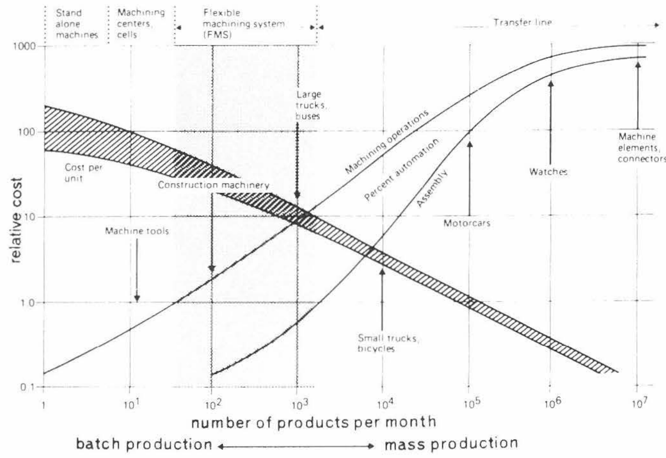

FIG. 4. Costs and automation versus volume (Source: Author, adapted from various sources)

solid-state monolithic integrated circuits and large-scale integration (LSI, VLSI) modern computers are of the order of 100,000 times *less* error prone than human workers [8]. In effect, the direction of technological change (in the industrialized countries, at least) is inexorably toward the substitution of computers and smart sensors for humans in all phases of the manufacturing process.

MICROELECTRONIC TRENDS

It is fairly obvious that computers and smart sensors, in the sense used above, must be based on the technology of microelectronics. The same is also true, incidentally, of Programmable Controllers (PCs), which are another key ingredient of advanced forms of automation.

Unit costs (i.e., costs per gate or bit of memory) have moved down essentially in step with the number of elements per chip. Chips are made by a complex, but highly automated and capital-intensive process in which direct (i.e., "hands-on") human labor plays almost no role. In fact, in modern plants humans must be rigorously kept away from the actual manufacturing steps because of the danger of contamination. The major elements of cost for electronic devices are now the design and the specialized capital equipment used in manufacturing.

The marginal cost of production is virtually the cost of materials only, which is negligible. The relative ease of copying successful designs explains why chipmakers try to amortize each new product in a very short time and why vicious price cutting tends to rapidly follow the initial introduction. The 256K RAM chip, first introduced to the market in 1983, is now selling at $4 or $.00156 per bit. Price trends for logical functions are shown in Fig. 5 and impacts on system costs are summarized in Table 2. In relative terms, costs have declined by a factor of about one million since the era of vacuum tubes.

It scarcely needs to be said that rapid technological improvements and corresponding cost reductions seem virtually assured for the next decade, at least, by the enormous research and development resources currently being invested in these areas. A number of major new technologies, including optical devices and organic chemical molecular (molecutronics) devices, now appear to be feasible and perhaps immanent.

[2]The cost of "logistics" including materials handling, storage, inventory control, and shipping, accounts for over 27% of manufacturing value added in Sweden [5]. A British study concluded that 19.5% of industrial labor costs are attributable to materials handling alone. For the U.S. logistics accounts for 22.5% of manufacturing value added [6].

[3]Including inspection, monitoring, rework, etc. One survey showed that quality control averaged 5.8% of sales, or roughly 11-12% of value added [7].

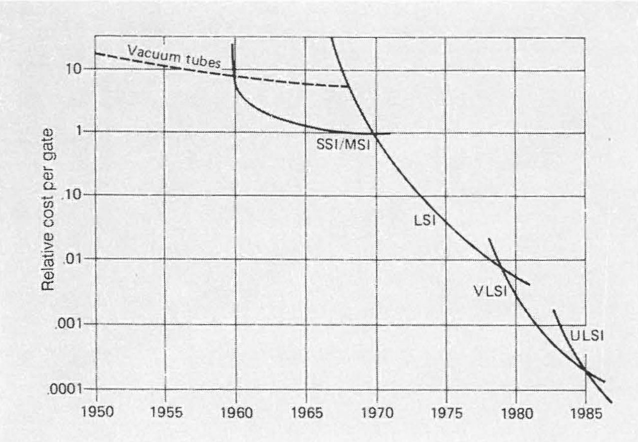

FIG. 5. Cost reduction for logical functions (Source: NIRA, 1985)

NUMERICAL CONTROL OF MACHINE TOOLS

The first step toward computer integration is the numerical (analog or digital) control of machines, especially metal cutting and forming machines. The first experiments were conducted in the period 1948–1953 under the sponsorship of the U.S. Air Force. Numerical controls (NC) were first offered commercially in 1955. A sequence of tool positions and feed rates was specified via a punched paper on magnetic tape. The early controllers were expensive and (by modern standards) difficult to program.

An early outgrowth of the NC technology was the development of the so-called machining center (MC) first introduced in 1958. These are multiaxis NC milling machines with the addition of automatic tool-changing capability. Machining centers are therefore capable of carrying out a sequence of cutting operations on a single part, using up to 50 different tools. They are thus ideal for small batch production of very complex metal shapes, for example, for the aerospace industry.

Application of large-scale integration (LSI) technology in the early 1970s, brought the costs down while simultaneously providing for vastly increased capability. A minicomputer costing $30,000 in 1974 is vastly outperformed today by a microcomputer costing $1500. Moreover, the increased availability of computer power in the early 1970s also permitted the introduction of far more flexible machine controls, known as computer numerical control (CNC.) Moreover, modular program packages were becoming available which cut programming time for CNC systems by a factor of 3 from 1971 to 1974 alone. This corresponds to increased use of CNC in larger-scale production applications (requiring bigger machines) and, especially, a growth in use of machining centers. The first generation of *adaptive* controls, featuring force feedback sensors in the workload to detect early signs of tool wear or misalignment, also appeared at that time. The advent of CNC also permitted another development: simultaneous control of a number of NC machines by a single computer, known as Direct Numerical Control (DNC). By the year 2000 comparable cost/performance reductions can be expected. The plain implication is that the electronic "hardware" costs are becoming negligible. In the 1990s and beyond, software will be the only cost factor affecting the choice between manual and CNC machine tools or other programmable devices.

The trend toward user-friendliness in controls has continued. So-called fourth generation languages of the 1980s exemplified by FOCUS, MARK V, RAMIS, IDEAL are far more user-friendly than COBOL or FORTRAN, the assembly languages of the 1960s. At this time, turnkey CAD systems were successfully introduced to the market giving rise to euphoric expectations of "intelligent factories" by the end of the decade [10]. By 1983 NC and CNC machines accounted for one-third of all *new* machine-tool purchases in the U.S., and over 103,000 NC and CNC machines were in service. Although this represents only about 5% of all machine tools in the U.S., it accounts for a much higher (but not accurately known) percent of output. Bearing in mind that many smaller and older machine tools are not used for production, and that many production machines are specialized and automatic, it is likely that NC/CNC has already achieved at least 25% penetration of its maximum potential, given the present emphasis on mass production in the U.S.

Table 2. Cost impacts of major microelectronic developments (Source: NIRA, 1985)

Evolutionary step	*Components to assemble*	*Component and assembly costs**	*Cost ratio*
1. Discrete-component systems (transistors, resistors, capacitors, etc.) DISCRETE	20,000–30,000	$6,000–$9,000	—
2. Integrated circuits (small-scale integration—less than 10 gates or bits of memory per device) SSI	350–500	$600–$900	10:1
3. Medium-scale integration (adders, counters, etc.—100 gates or bits of memory per device) MSI	125–150	$250–$450	20:1
4. Large-scale integration (microprocessors and custom LSI circuits—more than 100 gates or bits of memory per device) LSI	7–10	$100–$200	50:1
5. Single-chip microcomputer VLSI	1	$5–$10	1,000:1

*Excluding backplanes, cables, cabinetry, etc.

ROBOTS

Industrial robots with point-to-point controls for simple material handling tasks were first introduced commercially in 1959 and the first robot with path control capability appeared in 1961 (the Unimate). These robots were suitable for a number of purposes, including spray painting, spot welding, arc welding, and investment casting. Demand picked up somewhat in the early 1970s. By 1974, when CNC capabilities became available, there were about 1100 robots in service, and unrealistic expectations exploded, only to the disappointed. The number in service probably reached 25,000 sometime in 1986.

The slow pace of robot introduction in the U.S. prior to 1983 is essentially explained by the relative crudeness of the technology and the high cost of application engineering. The first practical assembly robots appeared only after 1980, and have not yet been widely accepted. It is much more difficult to find useful tasks for robots in older plants than it is to embed robots in newly designed factories. Even CNC robots are inherently difficult to control precisely because of the relatively large number of degrees of freedom involved (up to 7). Most robot manufacturers make it hard to integrate their robots with other machines under higher-level computer control by retaining secret proprietary operating systems. However, robots of the 1980s are substantially more accurate and better coordinated (e.g., two-hand control) than robots of the 1960s.

Programming languages for robots remain diverse and still relatively clumsy. Thus engineering costs for new applications tend to be quite high—up to two times the cost of the robot itself, which is a major impediment to small and first-time users [11]. Nevertheless, these difficulties are gradually being reduced as experience is accumulated. U.S.-based robot manufacturers produced 3060 robots in 1983, worth $330 million (they also lost money).

Robot capabilities are progressing, primarily because of improvements in controls and ease of programmability. A recent breakthrough in gripper design promises to reduce the amount of specialized engineering needed for each application. Electric motor drives are replacing pneumatic and hydraulic systems for robots requiring greater precision, such as assembly. Operating speeds are increasing, but not dramatically. Robots, in general, work at about the same rate as humans. Their economic advantage is greater reliability and timelessness. In principle robots can operate 24 hours a day, although this capability is seldom fully exploited. However, the major technical breakthrough of the 1980s is the addition of vision and/or tactile sensors and adaptive (feedback) control to robots.

FLEXIBLE (BATCH) MANUFACTURING: FMS AND LS/FMS

So-called flexible manufacturing systems (FMS) have attracted much attention since the first attempt to combine several NC machine tools with an automated materials-handling system under computer control (ca. 1967). Applications have focused on mid-volume batch production of moderately complex parts at volumes of 2000 to 50,000 units/year.

In a modern sophisticated FMS, palletized workpieces of different types randomly travel between and are processed at various programmable, multipurpose machine tools and other workstations. Parts flow through the system according to individual processing and production requirements, under automatic computer control.

The flexibility of an FMS is only relative (e.g., to a special purpose machine). It is also not achieved without cost. A transfer line and an FMS both need basic machine drive workheads, materials handling system, and tools. But an FMS requires variable speeds and cycles, numerical (i.e., digital) controls and a supervisory computer to coordinate cell operation (see Fig. 6). In addition to the added hardware cost of an FMS is the cost of the systems software and the specialized programs need to implement a particular task. In a more sophisticated FMS with automated inspection or adaptive control capabilities the cost of sensors and vision (or tactile) information processing must also be included. It is clear that the implemented cost increases as the level of

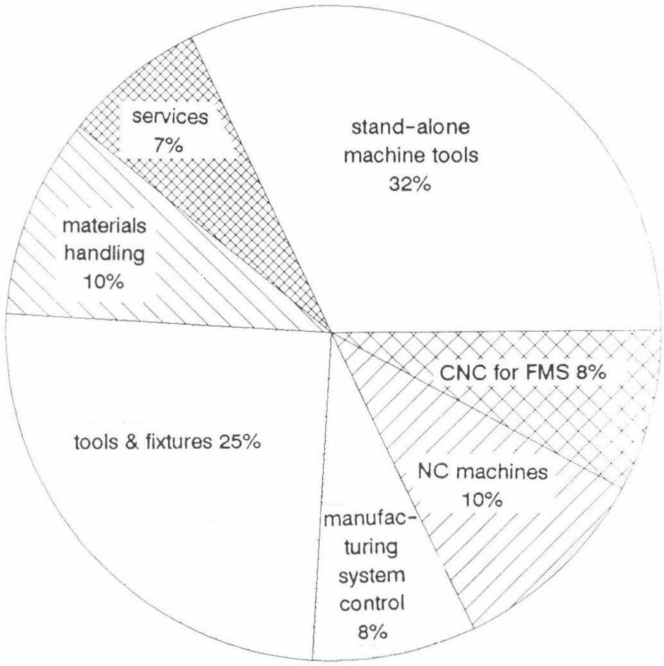

FIG. 6. Manufacturing system (FMS) hardware cost (1984) (Source: Data from Kearney & Trecker, Inc.)

control (Table 3). Numerical control (NC) capability adds about one-third to the per-spindle cost of a typical machine tool, and the provisions for integrating CNC into an FMS adds another 20% roughly.

This cost comparison is only meaningful if we compare equipment manufactured on the same scale of outputs. Relative costs, too, will change over time. Control-related components of flexible manufacturing systems are rapidly dropping in price, as pointed out earlier. As the price of these components decreases, so will the overall cost of the FMS.

An obvious implication of the foregoing discussion is that the hardware cost of flexible factory automation can be cut sharply (perhaps three-fold or more) by deliberately using more standardized equipment modules that could themselves be manufactured in much larger batches. Rapid Japanese penetration of the U.S. CNC machine tool market since 1980 seems to be based on this strategy. These modules will necessarily be quite generalized in capability, that is, with variable speeds and cycles and an exogenous system of electronic controls. (Determination of the appropriate control settings is done off-line, with the assistance of simulation models.)

Here the essential difference between small batch manufacturing in a multiproduct plant and large-scale or mass production of a single product becomes apparent. In small batch production (job shops) there is really no need to synchronize the operations of different cells. Coordination can be rough, since no run is very long and workpieces in process can normally wait until a suitable machine becomes available for the next operation. Machine utilization can be

Table 3. Cost of machine tool controls ($ × 10³) in FMS

Fixed sequence	100 ± 25
Variable sequence	110 ± 25
NC (Tape)	125 ± 25
CNC	150 ± 25
Adaptive, with sensing	175 ± 25

increased at the expense of work-in-progress inventory, and vice versa. The optimum balance is determined by experience, or with the help of scheduling models. But machine utilization is likely to be quite low and inventory of work-in-progress is likely to be high even in a well-managed job shop. Idle machines or exceptional delays are the major clues to shop schedulers to modify normal processing sequences. When such problems are persistent, the remedy may be to add an additional stand-alone machine, or possibly to eliminate one that is unnecessary.

In a hard-automated large batch (mass) production environment, however, only one product is being made at a time and the sequence of operations is fixed. In this situation the ideal situation is one where the inventory of work in progress is, essentially, one workpiece per workhead. In principle, machine utilization is very nearly 100% when the plant is operating except for setup periods and tool changes or other scheduled maintenance. Of course, a breakdown at any point in the fixed sequence causes the whole line to stop. In an imperfect world this limits the number of machine operations that can be linked safely in sequence without a buffer. Such a linked set of machines constitutes a "cell" in the mass production environment.

The generic large-scale FMS (LS/FMS) will therefore consist of a number of "cells" buffered by intermediate storage, but operating synchronously *on the average*. The target operating mode would be such that the number of workpieces stored in each buffer unit fluctuates around half of its maximum storage capacity.

It can be assumed that each machine is controlled by a microprocessor which, in turn, communicates with a minicomputer at the cell level. The machine microprocessor contains a stored program of instructions for the machine, downloaded from the cell controller. Sensory automation monitors performance in real time. Any deviation from the expected status of the machine/workshop during processing would trigger a slowdown or stop which is signaled to the cell controller.

The cell controller coordinates materials handling functions within the cell and provides the "beat" that synchronizes the individual machine programs (as a conductor synchronizes the musicians in an orchestra). Again, sensory feedback data monitors cell performance in real time, and deviations from the norm can result in a programmed shutdown of the cell, and an automatic maintenance call. The cell controller, in turn, communicates directly with neighboring cells in a "distributed control" scheme, or with a higher level supervisory computer that coordinates other cells and buffers, as well as overall materials handling functions. If one cell is down the supervisory computer may instruct neighboring cells to continue to function temporarily, taking workpieces from buffer storage or feeding them into buffer storage. In a very sophisticated LS/FMS there may also be several cells, in parallel, carrying out the same sequence of operations. In this case the supervising computer might bypass one cell and temporarily speed up the others to compensate. This would increase the rate of tool wear and result in earlier tool changes in the affected cells, but this would often be cheaper than simply reducing production for the plant as a whole.

Evidently, the computerized operating system for a LS/FMS in large batch production mode would be quite complex, though qualitatively different from the operating system for a multiproduct "parts-on-demand" plant. In many respects, the control problems are similar to those encountered in a traffic flow network or continuous process plant, that is, the buildup of nonlinear transients resulting from feedbacks in the system. The analogy between traffic flow and parts flow and phenomena collisions and congestion is quite close.

A recent report by the Economic Commission for Europe (ECE) shows extremely rapid growth in the number of first-generation FMS installations since 1975. At the beginning of 1985 there were 46 FMS's in the U.S. (compared to four at the beginning of 1975) and around 250 in the world [12]. As shown in Fig. 7 the rate of growth appears to be accelerating. (As of 1985 the ECE counted 100 FMS's in Japan, 60 in the USSR, and 36 in West Germany [9].) The technology now appears to be reasonably well established. A recent forecast by the Yankee Group (cited in reference [13]) puts the likely number of FMS's in the U.S. by 1990 as 280. (Many of these are already planned or on order). The U.S. market for FMS is expected to increase from about $262 million in 1984 to $1.8 billion by 1990.

The first generation FMS systems are largely custom designed to produce a "family" of parts in small-to-medium batch sizes. Once built, they are not particularly adaptable to other sizes or shapes. However, as adaptive machine control technology becomes increasingly practical in the 1990s and machine control software packages become more powerful and easier to use, more and more new and virtually unmanned (second generation) plants will be built to make products that are less standardized and subject to more frequent design change.

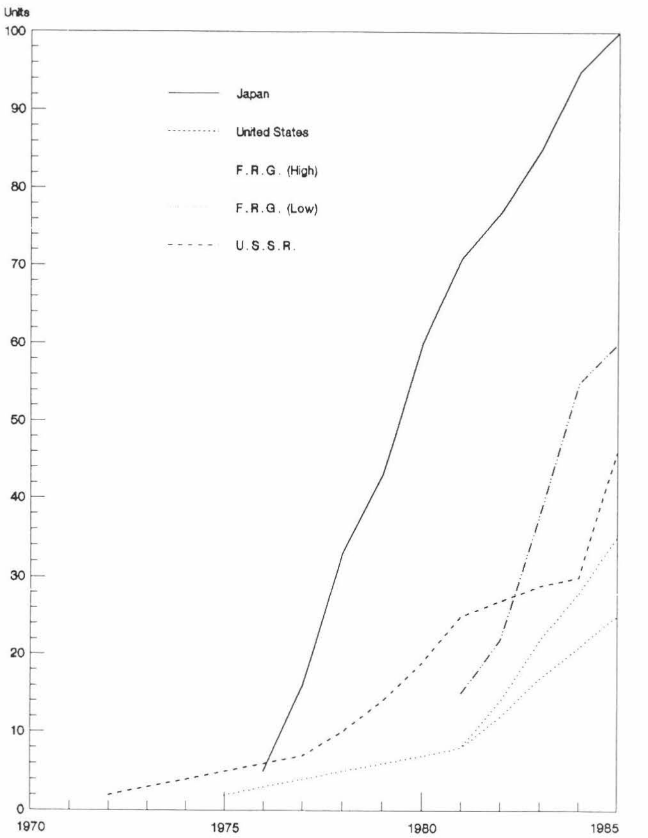

FIG. 7. Growth of FMS in the Federal Republic of Germany, Japan, the USSR, and the United States (Source: ECE 1986, Fig. III.1 [13])

CAD/CAM

Computer-aided design/computer-aided manufacturing (CAD/CAM) is very nearly self-explanatory, except perhaps that it is unclear where NC, CNC, or DNC become CAM. Roughly speaking, CAM systems are high-level supervisory systems that may carry out planning and scheduling functions for a plant and generate programs for individual machine tools and/or cells. Under present conditions CAD and CAM are largely separate, but it is clear that as designs (and design changes) are increasingly digitized the blueprint stage will eventually be bypassed. Moreover, the detailed planning of a manufacturing process (e.g., a sequence of steps), starting from a set of design drawings and specifications will increasingly be automated. Table 4 illustrates the progressive complexity of CAD applications with increasing emphasis on expert systems.

CAD had its beginnings in proprietary systems developed in-house by large aerospace manufacturers such as McDonnell-Douglas and Boeing. These early systems used mainframe computers. However, CAD reached the market place around 1970 when the first turnkey systems became available. The industry grew rapidly, passing the $25 million mark in 1977 and the $350 million level in 1979. At that time virtually all CAD system producers were in the U.S. Worldwide demand continued to grow rapidly, from $592 million in 1980 to an estimated $2.8 billion in 1982 and $3.5 billion in 1985 (of which $2.8 billion was supplied by U.S. firms). At least a $10 billion market is expected by 1995 [15].

Unit prices are dropping rapidly. The average CAD system installed in 1980 cost close to $500,000 million when 1500 systems were installed. In 1985, 11,000 were installed at an average cost of just under $400,000. Most of these systems use 32-bit minicomputers. There were about 18,000 CAD installations in the U.S. in 1985, and probably 25,000 worldwide, with an average of four workstations per system.

It is expected that unit prices of systems sold in 1995 will be about 20% of 1987 prices, with 70% of the performance. This is due to the increasing use of CAD adapted for 16-bit personal computers. It is estimated that 90% of CAD systems sold will be on 16-bit personal computers by 1990 [16].

There is much less information on the CAM market, since it is extremely diverse and most of the work in this field is undoubtedly in-house software development for specific applications. It is likely that the expansion of CAM applications is keeping pace with CAD. However, until CAD and CAM are truly linked into one system, the dream of "industrial boutiques" producing parts on demand will not be realizable.

Table 4. CAD technology (Source: Chorafas, 1987)

Year	*Capability*
c. 1961	CAD, 20, Single Terminal
	Mainly Drafting
c. 1963	CAD, 2½D, Multiple Terminals
c. 1966	CAD, 30, Full Scale Industrial Applications
	Emphasis on Design
c. 1968	CAD, Finite Element Analysis
c. 1970	Simulation Capability
	Experimentation Capability
c. 1972	Integrated Engineering D8
c. 1974	CAD/CAM, Bill of Materials, Integrated Engineering and Manufacturing D8
c. 1978	CAD/CAM Networks, Online Integrated Engineering and Manufacturing D8 with Dynamic Configuration
c. 1982	Integration of Engineering and Manufacturing D8 with MIS
c. 1984	30 Geometric Modeling
c. 1986	Integration with DSS

MACHINE VISION AND TACTILE SENSING

Machine vision systems became commercially available in the late 1970s and a large number of new startup ventures entered the field after 1980. Vision technology is currently "hot" and the apparent rate of technical progress is very high, as suggested by Fig. 8. The first generation of vision systems required a fairly powerful minicomputer, which specialized software to process visual information (pixels/s) and discriminate patterns of shapes by "neighborhood." These early systems were both crude and very slow. Vision technology of the mid-1970s was binary. It detected and classified "blobs" based on their shapes, using statistical pattern recognition. A second generation of vision systems capable of discriminating gray scales and more sophisticated syntactic pattern recognition began to be available to commercial users in the early 1980s. Future systems will eventually add color, stereo, shading, texture, motion, shadows, and so on. However, it is not at all clear how soon these capabilities will appear in affordable commercial systems. Nevertheless, adaptive systems employing sensory feedback, primarily vision and/or touch, are going to be the key to truly computer-integrated fifth generation automation, as summarized in Table 5.

The key to improve performance of vision systems is parallel processing and the key to reduce costs is customized VLSI chips. Such chips began to be produced in quantity by

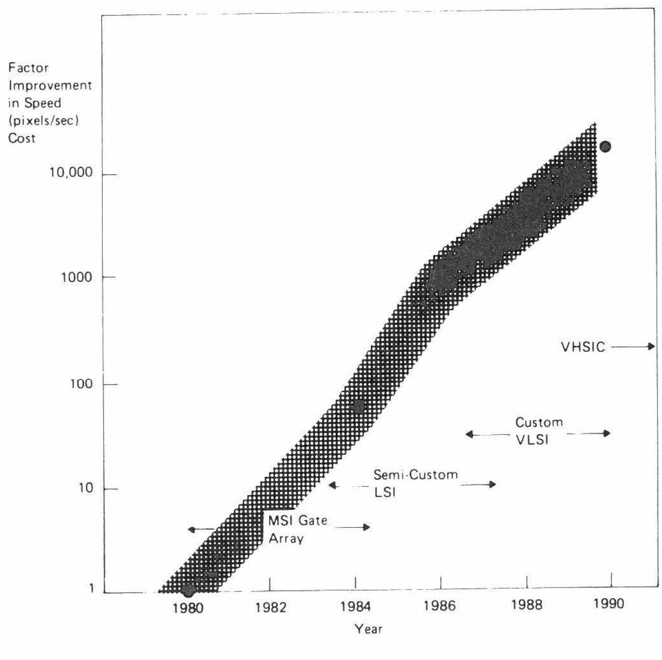

FIG. 8. Estimated improvements in speed (pixels/sec)/cost/ratio for neighborhood processing (Source: Funk, 1984 [17])

1985. Tactile sensors will require parallel processing very similar to that needed for vision systems. It thus seems quite safe to project that adaptive control for both machine tools and robots using vision and/or tactile sensors will become a practical reality by 1990 and will be fairly widespread by 2000, as shown in the last column of Table 5.

Current applications of vision systems are primarily for the control of manipulation tasks (such as drilling, routing, riveting, spot welding, soldering, sorting, palletizing, and assembly) and for inspection. Examples of both types of applications (ca. 1985) are listed in the appendix. In the case of inspection, the simplest use of machine vision is to check part dimensions against a stored template. Other types of inspection already exemplified include checking for integrity, color, orientation, reflectivity (shine), and so on. Automated inspection may become far more sophisticated in a few years, however, as judgment capabilities using artificial intelligence are built into the vision systems.

At present, most applications of vision (or taction) require substantial front-end investments in applications engineering. Moreover, they are still quite limited in their capabilities, primarily because of difficulties in interpreting a visual scene. However, rapid technological improvements in the area of sensor sensitivity, software programmability and user friendliness, together with expected rapid cost reductions, will make automated 100% inspection a practical reality for most kinds of large volume production by the year 2000 (if not sooner).

Table 5. Five generations of automation

	Premanual control	*First (1300): Fixed mechanical stored program (clockwork)*	*Second (1800): Variable sequence mechanical program (punched card/tape)*	*Third (1950): variable sequence electromechanical (analog/digital)*	*Fourth (1975): variable sequence digital (CNC) (computer control)*	*Fifth (1990?): Adaptive intelligent (AC) A.I. (systems integration)*
Source of instructions for machine (How is message sent?)	Human operator	Machine designer/builder	Off-line programmer/operator records sequences of instructions manually	On-line operator "teaches" machine manually Off-line programmer prepares instructions	Generated by computer, based on machine level stored program instructions modified by feedback	Generated by computer, based on high-level language instructions, modified by feedback
Mode of storage (How is message stored?)	NA	Built-in (e.g. as patterns of cams, gears)	Serial: patterns as coded, holes in cards/tape or as pre	Serial: as mech. (analog) record (e.g., on wax vinyl disc) Serial: as purely electrical impulses (e.g., on magnetic tape)	In computer memory as program, with branching possibilities	In computer memory as program with interpretive/adaptive capability
Interface with controller (How is message received?)	Mechanical linkage to power source	Mechanical: machine is self-controlled by direct mech. links to drive shaft or power source	Mechanical: machine is controlled by mech. linkage actuated by cards via peg-in-hole mechanism	Electro-mechanical: controlled by valves, switches, etc. that are activated by transducers—in turn, controlled by playback of recording	Electronic: machine reproduces motions computed by program, based on feedback info.	Electronic: (as in CNC) machine adjusts to cumulative changes in state
Sensors providing feedback?	NA	NA	NA	NA	Narrow analog (converted to digital) (e.g., voltm./strain gage) Spectrum digital (e.g., optical encoders)	Analog or digital, wide-spectrum, complete descriptions visual, tactile, requiring computer processing
Communication with higher-level controller?	NA	NA	NA	NA	NA Optional primary program downloaded from higher level	Essential, because micro-processor at machine level must pass visual and tactile info to higher levels to coordinate High level controller has learning ability

WHAT NEXT?

It is very difficult to estimate the maximum level of penetration of robots, FMS, CAD/CAM, and vision systems. In the case of robots, a simplistic calculation based on the substitution of one robot for every two workers in the semiskilled machine operative category (excluding transport operatives) suggests an ultimate potential of 3 to 4 million robots in the U.S. manufacturing sector. This is much too high a number, if the potential for 24 h/day operation is realized. On the other hand, robots will not replace all operatives, especially in smaller firms, for at least 30 to 40 years. Any such massive replacement also presupposes dramatic improvements in robot programmability and performance. In fact, the full potential of robots (and, for that matter, computers) will not be realized until interactive verbal communication in natural language becomes feasible. This has been an objective of research in computer science for many years, but a breakthrough is still very remote. It appears quite safe to assert that this capability will not be a practical reality until well beyond the year 2000.

All things considered, the present level of penetration of robots, FMS, CAD/CAM, and vision is probably not more than 1% of the maximum potential, and possibly less. This implies, among other things, that despite a considerable history, nothing much can be inferred about future rates of growth of the sectors involved. The technology is still too primitive and unpredictable for either technology innovators or their customers to make reliable projections as to future price/performance ratios. Experience from the past does suggest, however, that the difficulties are easily underestimated. In the field of automation, market forecasts have been consistently overoptimistic.

Several fairly strong conclusions can be drawn, nevertheless. One is that human labor, especially in the operative category will continue to be eliminated from manufacturing, primarily to increase product quality and reliability while cutting costs. This trend is well under way. It seems quite clear that direct manufacturing labor will decline to an insignificant level before the second or third decade of the next century. This has obvious implications for unions, educational institutions, and government at all levels.

A second conclusion that also seems equally robust is that the software component of capital will continue to grow in importance vis-à-vis the "hardware" component (Fig. 9). The electronic hardware component (computers and electronic controls), which grew rapidly in the 1960s and 1970s, will not continue to grow so fast, because of declining prices. In fact, by the year 2000 software is likely to be so important that it will have to be explicitly measured. While no such measures presently exist in the national accounting system or the SIC, some indicators are available. It is now a widely accepted rule of thumb that the ratio of software to hardware costs average around 3:1 for any newly computerized system. This is roughly the reverse of the rule of thumb in the early 1960s. Issues of software in flexibility software compatibility and software productivity are now becoming dominant considerations in designing major systems. An increasingly important objective of research will be the development of intelligent (i.e., adaptive) programs and software to generate software.

A third and related conclusion is that competitiveness in manufacturing industry will increasingly depend on the quality of a firm's production software. Software engineering (and software security) will become increasingly important functions for a world-class manufacturing firm. Security will become a far more complex problem in view of the ease of transferability of software.

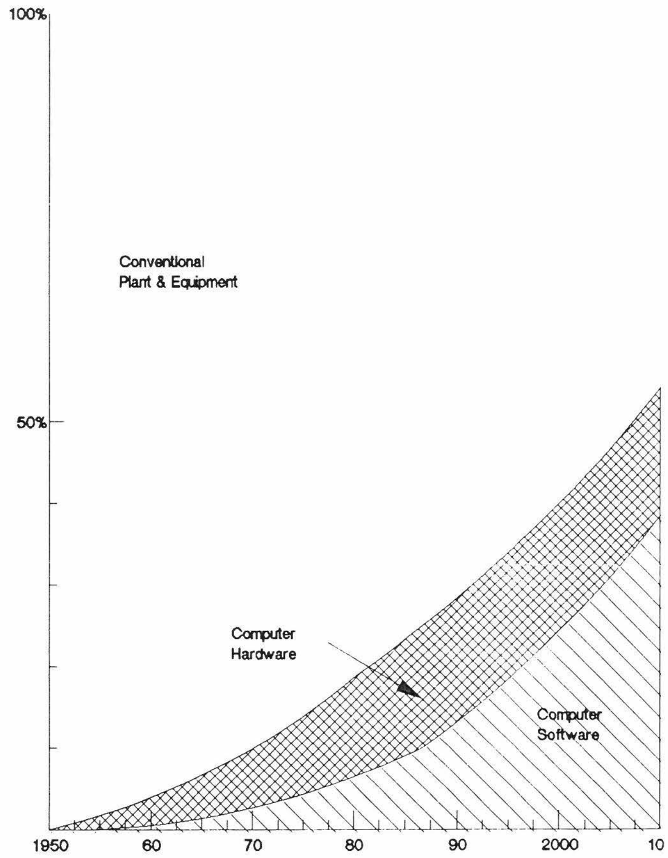

FIG. 9. Composition of capital stock (value)

A more speculative conclusion concerns the "North-South" economic competition. Recent trends indicate a fairly rapid movement of manufacturing away from the high-wage industrialized countries, especially to the perimeter of Asia. This has been particularly noteworthy in the area of electronics assembly and garment manufacturing. It would seem, however, that as the direct manufacturing component of total cost declines, large firms will be increasingly disinclined to fragment their operations in this way, with the accompanying penalties in terms of more complicated logistics, inventory controls and so on. The logic of the situation would seem to indicate a future trend toward the co-location of production with major markets. Flexible automation seems to reduce the benefits of extremely large-scale production facilities (dictated, in the past, by the costs of "hard" automation). This, in turn, suggests a more dispersed, decentralized production system with many more small plants, located near markets. In effect, production for the U.S. market will be increasingly located in the U.S., and similarly in the developing countries. International trade in standard manufactured goods will not grow as rapidly in the future as it has in the recent past.

The competitive advantage of low-wage countries may also be diminished to the extent that by depending more on human labor than the developed countries, they may find themselves unable to produce goods of the requisite international quality standards. Thus, it seems likely that increasingly after the 1990s low-wage countries will have only limited access to the markets for manufactured goods in the wealthier countries, primarily at the low end of the quality spectrum.

ACKNOWLEDGMENT

This paper borrows quite heavily from earlier collaborative work. In particular, I wish to acknowledge significant intellectual contributions by Steve Miller and Jeff Funk, who wrote Ph.D. dissertations under my direction on economic impacts of robot machine operation and assembly, respectively. I also want to acknowledge the contribution of Susan Bereiter, who did some serious thinking on the implications of large-scale flexible manufacturing system (LS-FMS). She is now completing her Ph.D. under Steve Miller's direction. MR

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APPENDIX: EXAMPLES OF APPLICATIONS OF VISION SYSTEMS IN INDUSTRY

User	*Sensor-controlled manipulation applications*	*Vendor*
Westinghouse Winston-Salem, NC	Robot-vision system to pick & place and inspect turbine blades.	In-house with C-MU
GM	Consight I Vision-Robot System Picks randomly placed parts off of moving conveyor.	In-house
General Motors Janesville, Wis.	Light-stripe sensor or Robot wrist (Robo-Sensor) for welding of J-cars.	RVS
Lockheed-GA	Robot-based assembly of cargo aircraft using the Robo-Sensor. Includes: light projector, wrist-mounted camera, computer, software. Hardware cost: $35-$70,000.	RVS
Lockheed-GA	Assembly of internal part for C-130 Hercules Cargo aircraft.	RVS
Kawasaki	Laser-based vision system used for path correction in arc welding of motorcycle parts.	?
Matushita Electric Co., Japan	Robot-vision system for vacuum cleaner.	?
Texas Instruments Lubbock, TX	Calculator assembly lines with robots.	?
United Technologies, Sikorsky Aircraft	Drilling and riveting for aircraft assembly. *Includes*: ASEA, 1Rb-60 robot mounted on track, DEC LSI 11/23 as system controller, various contact and vision sensors.	?
Hitachi	Robot-vision system which detects holes for assembly. *Includes:* solid state optical sensors, CCD-type TV camera mounted on robot arm.	?
Western Electric Atlantic Plant	Color-sorting of telephone receiver caps into bins. (6500/h). Uses photo diodes and color filters. 99.9% accuracy	?
GM Warren, MI	Stacks random mix of pre-taught parts. Uses light stripe, PUMA robot system, 3 DEC LSI 11's, video camera, and VAL programming language.	
	Inspection Applications	
Unknown	Automatic inspection of welded automobile wheel hubs. Checks for integrity of structure.	MIC
Unknown	Off-line floppy-disk jacket inspection, manually operated. Checks dimensions.	MIC
Unknown	Automatic identification of various models of electrical circuit breakers on a conveyor belt. Checks product type.	MIC
Unknown	Automatic inspection of ceramic supports for cathode ray tubes. Checks for dimensions.	MIC
Unknown	Automatic inspection of ray tube displays. Checks for integrity of features.	MIC

APPENDIX continued

User	*Sensor-controlled manipulation applications*	*Vendor*
Unknown	Automatic inspection of spark plugs on a moving conveyor belt. Checks dimensions.	MIC
Unknown	Automatic fluoroscopic inspection of cut and welded parts for stress cracks. Checks integrity of internal structure and dye is used to make flaws fluoresce.	MIC
Unknown	Automated inspection of glass CRT necks, uses a UV-light source to image internal defects. Checks intergrity of internal structure.	MIC
Unknown	Automatic inspection of plastic sutures. Checks integrity and dimensions.	MIC
Unknown	Automatic inspection of automotive wheel hubs for conformance to forged dimensions prior to subsequent machining operations. Checks integrity.	MIC
Unknown	Inspection of valve bodies for automatic transmission. Vision is interfaced with robot. Software mask examines internal details. Exact positioning is required. Checks dimensions of a single type of product.	MIC
Unknown	Automatic inspection systems for precision components. Vision is interfaced with a robot. Checks dimensions.	MIC
Unknown	Gray-scale imaging system for paper-cup packaging. Checks for number of cup lips.	Octek, Inc.
Cummins	Inspection of engine blocks. Uses light striping.	RVS
Hitachi Japan	Automatic Reticle System (ARI) which uses semiconductor photomask inspection for products.	?
Delco Electronics Kokomo, IN	Determines chip position and orientation, inspects chip structurally, allows for proper alignment of test probes with chip contacts.	In-house
Honeywell	Robot vision station for solder joint inspection of circuit boards. Uses TV camera for 2-D image, PUMA 560 robot, Autovision II, plus micro-computers.	In-house
	Combined sensor-controlled manipulation and inspection application	
Automatix Corp. Billerice, MA	Robot-vision system for assembly and inspection of keyboard arrays. Uses the Cybervision Assembly Station and the Autovision II processor, with the AID 600 robot and AI 32 controller.	Automatix

Key to Vendor Abbreviations

CMU: Carnegie-Mellon University, GM: General Motors, MIC: Machine Intelligence Corp., RVS: Robot Vision System, ?: Vendor of system not specified in literature

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Technology Forecast For CIM

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This paper identifies a number of aggregated ("top down") measures of technological capability and penetration for Computer-Integrated-Manufacturing (CIM) and discusses the problems of forecasting. The four proposed measures discussed in detail are as follows: 1. Capital flexibility: the ratio of software costs to total invested capital: 2. Machine utilization as a fraction of a 24-hour day (to reflect unmanned operations); 3. Fraction of NC tools that are not 'stand-alone' but are controlled by higher level computers; and 4. Order-to-delivery time. Rough estimates of recent and likely progress in the first three measures are given.

INTRODUCTION

There are two main approaches from which any forecasting problem may be viewed. These may be termed *top down* (or macro) and *bottom up* (or micro). The top-down approach begins with a broad characterization of the technology in terms of its function, and proceeds to attempt to identify a suitable quantitative measure of performance or, failing that, a set of discrete stages or milestones, together with estimates of when they will be achieved, assuming current rates of investment in R&D continue. The bottom up approach, by contrast, seeks to decompose the overall technology into its systems, subsystems, components, and so forth. It then proceeds to identify suitable quantitative measures of performance for each of these elements, and finally to re-aggregate them. In this paper we will address the forecasting problem from the first of these directions.

An inevitable source of some confusion must be acknowledged. In principle we would like to draw a clear distinction between changing technological capabilities and adoption/diffusion/penetration of existing technologies into new areas of application. In the case of CIM these two processes proceed simultaneously and to some extent indistinguishably. The technology of computer integration cannot really be said to exist for a given manufacturing sector and product until it has been demonstrated in practice at least once. The problems in different segments are sufficiently different so that it is sometimes very difficult to extrapolate from one case to another. Because of this difficulty, however, some measures which appear to be measures of diffusion are, at least indirectly, also surrogate measures of capability (and vice versa).

MANUFACTURING FROM AN INFORMATION PERSPECTIVE

It has been argued previously that manufacturing can fruitfully be viewed as a process of embodying useful information in materials [1]. To be precise, the "value added" to a material or workpiece corresponds to the addition of some kind of information. The term "information" is used, here, in its technical (Shannonian) sense, meaning, roughly, distinguishability from the environment or surroundings. Where the term *entropy* can be defined, information can be defined as its negative (negentropy). An exposition of this way of looking at economics has been given elsewhere and need not be discussed at length here [2].

In fact, it is helpful to categorize embodied information into two types: (1) **thermodynamic** information and (2) **morphological** information. The first is a function of physical and chemical composition and micro-structure. It can be computed quantitatively by methods described in standard textbooks, but which need not be discussed further here. Suffice it to say that every stage of materials processing, from extraction and crude separation through smelting, refining, alloying or chemical synthesis can be described thermodynamically as the creation of entropy in the environment and negentropy (or information) in the materials being separated, refined, etc.

The second type of information is essentially a function of geometrical shapes and forms. It depends, of course, on the precision with which shapes or forms are specified. Since the more conventional usage of the term information—that which is conveyed by words or pictures—refers to symbols and patterns, it is evident that the kind of information found in a library or a computer program is entirely of the morphological kind. Morphological information also presumably corresponds to negentropy, but there is no advantage in adopting thermodynamic language, except to the extent that it facilitates conceptual clarity. For our purposes, the morphological information embodied in a material as a result of some metal-working process can be thought of as the minimum amount of information needed to describe the process or, in effect, to instruct a numerically controlled machine tool to carry it out. It must be emphasized that the minimum, which is the amount embodied, may be considerably less than the actual amount of information in a practical computer program.

The output of various industrial sectors can also be classified in terms of the kind of information embodied. Evidently the metal-working sectors of interest to us (SIC 33–37) are exclusively concerned with shaping, forming and assembly, i.e., with morphological information. In traditional manufacturing the actual shape-changing operations are done by machines, but all of the control decisions are made by human workers. The rate at which human workers can process sensory inputs and generate information outputs (e.g. instructions for machines) is biologically limited [1]. Moreover, ergonomists have observed that the human error-rate, or the fraction of information outputs that is garbage, tends to rise sharply as the worker approaches maximum output, as indicated schematically in Fig. 1. Since the economic value of output information—expressed as patterns or shapes—is likely to decline as a high power of the error or garbage fraction, there is a high incentive for increasing accuracy (decreasing defects).

In view of the above points, the function of manufacturing, taken as a whole, can arguably be described in terms of maximizing the useful (i.e. correct) morphological information embodied in materials by the manufacturing process, while minimizing the incorrect information, or defects. Since two objectives cannot simultaneously be optimized, however, we must devise a single composite objective function. Such a function might be of the form

$$U = PuH + PgG \quad (1)$$

where H is the quantity of useful (i.e. correct) morphological information embodied in the products of the metal-working sectors during a unit of time, G is the quantity of incorrect (garbage) information embodied, and Pu and Pg are the unit prices of useful information and garbage information (errors), respectively embodied in products. The utility U refers to the given unit of time. The expression (1) above can obviously be expanded into summations over specific types of manufactured products.

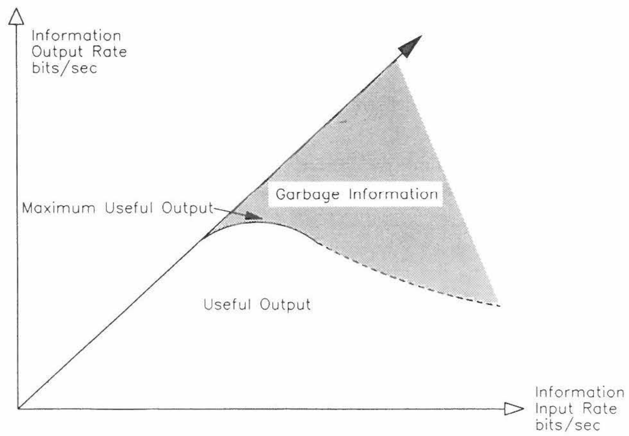

Fig. 1. Information Overload Phenomena

Of course, the unit price of garbage information is negative. That is to say, misinformation (errors and defects) creates a cost, and—in many circumstances—the cost of detecting and correcting one error is significantly larger in magnitude than the unit price of "virgin" useful information. This reflects the well-known fact that a single defective part embodied in a larger system may suffice to cause that system to fail, or necessitate major additional expenditures for rework and repair. In any case, the fact that some errors and defects are inevitable introduces the need for pervasive and continuous error detection and correction activities. Inspection and repair/rework becomes a major element of cost in complex production systems.

The problem is that failures tend to cascade. According to a nursery tale: "For want of a nail, the shoe was lost; for want of a shoe, the horse was lost; for want of a horse, the rider was lost; for want of a rider the message was lost; and for want of the message, the war was lost." The modern version (unfortunately) might be: "For want of an 0-ring the Challenger and its crew of astronauts was lost; for want of the Challenger the U.S. manned space program has lost billions of dollars and several years." It may, indeed, be permanently crippled.

The severity of the error-defect problem is essentially proportional to the complexity of the final product. If one is manufacturing nails, the cost to the user of a defective nail is essentially the cost of the time to recognize it and discard it. The cost of a defective watchspring is comparable, as long as the defective spring is recognized before it is put into a watch. If the defect causes the watch to fail later, the much greater cost of dismantling the watch and putting it back together must be added. In larger systems, the cost multiplication continues. A defective chip in a P.C. board will necessitate only some manual rework if it is detected before the board is installed in a navigational computer. If the computer fails in flight, however, the result could be catastrophic. It follows, therefore, that P_g is some function of the complexity of what is being produced. Evidently, complexity is an important attribute of technology. See Fig. 2. Further discussion can be found in [3].

As yet, we have no good measure of complexity for use in estimating the cost of defects and garbage information. Complexity, itself, is a measure of structural (morphological) information embodied in the completed product. For a simple product like nails, it is essentially the same as H in the above formula. For multi-component products, of course, the complexity of the product as a whole corresponds roughly to the information embodied in all the components individually, plus the structural information needed to assemble them.

Can complexity be measured in practice? A complete and consistent set of rules for adding up the information contents of the parts to make the whole involves a number of special considerations, such as symmetries [1]. As a first approximation, however, one might measure complexity of products in terms of the number of discrete parts, times some measure of the complexity of the average part. In the case of a purely mechanical system, the complexity of a rotational or prismatic part can be estimated in terms of the number of cylindrical or flat surfaces and the precision with which each of them is

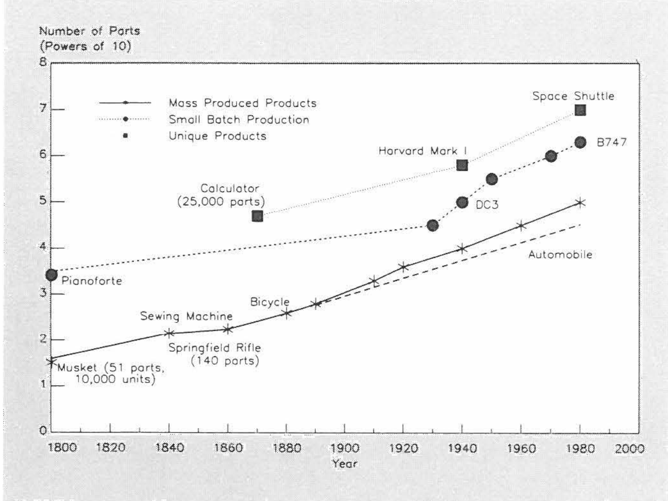

Fig. 2. Complexity Trends

specified in the design [1]. In the case of higher-order curved surfaces, such as turbine blades or propellers, a more sophisticated mathematical analysis is needed. For microelectronic parts (chips) similar considerations appear to be applicable to the individual circuit elements themselves. Further research is obviously needed to develop such measures into useful analytical tools.

MORPHOLOGICAL INFORMATION EMBODIED BY CUTTING AND FORMING OPERATIONS

In principle, it would seem, all the variables in the simple utility function for manufacturing (equation 1) can be estimated from technical data, except for the two price coefficients. It is illuminating to focus specifically on the shaping and forming component of manufacturing.[1] Let us note the time dependence explicitly and write

$$H(t) = A(t)M(t) \tag{2}$$

where $A(t)$ is the amount of morphological information embodied in finished materials per unit mass (e.g. ton) by the metal-working sectors and $M(t)$ is the tonnage of materials processed, in year t. Obviously $A(t)$ constitutes a rather general measure of technological capability. Again, the expression (2) can be expanded into summations over types of materials and types of products. However, so far, we have no plausible independent measures of information embodied in materials. To obtain such a measure, it is necessary to expand the magnification of our field of vision by examining the manufacturing process in more detail.

Within the metal-working sectors, it is reasonable to subdivide all processes except assembly and inspection into unit operations, each of which is performed by a machine. The major categories are metal-cutting, metal-forming and joining (e.g. welding) machines. By far, the largest number of machines in use belongs in the first category and the majority of them are turning machines, drilling machines, milling machines, grinding machines and sawing machines. Among metal-forming types, by far, the largest is presses, followed by bending machines and punching machines. Turning machines generate cylindrical sections (external or internal) or profiled surfaces with rotational symmetry, such as screws. Milling machines generate flat surfaces, as well as almost any type of curved surface. Grinders are also used for many surface geometries. Gears—a specialized subset—are made by a variety of specialized machines that could technically be classed as millers, planers, shapers, hobbing machines and generating machines. Saws (along with flame cutting torches) are mainly for crude cuts subject to subsequent finishing.

It is argued here that each machine operation embodies a certain amount of morphological information in the resulting surface, depending on its geometry [1]. An average information output for each operation, for each type of machine, should be possible to determine by a combination of empirical research and theory. Thus, the information required to specify a simple flat surface may be computed from the information required to specify a plane intersecting a solid. Depending on the required accuracy, this can be determined in bits [1].

Roughly, the amount of information per operation (i.e. per surface generated) is 10 bits per dimensional control parameter or coordinate that must be specified plus a contribution from the information embodied in the machine's design that enables it to "know" that a given parameter refers to a particular geometrical family of shapes (e.g. bevel gears). The amount of information implicit in this knowledge is, at the moment, difficult to estimate. Several approaches, however, are currently being explored.

Milling operations might require as few as 4 parameters to specify (for a flat surface), but a more general case would be to specify 13 parameters, consisting of 3 initial position parameters and 3 feed rates for the cutting tool and the same again for the table or pallet, plus spindle speed. As in the case of turning machines, the feed rates can be functions of time for cutting very complex asymmetrical, curved surfaces such as a turbine blade. This, with the grinding machine, is the most flexible type of machine tool. It is capable of producing virtually any surface, interior or exterior.

A typical lathe operation might require 7 parameters, corresponding to initial tool position (X-Y-Z) and feed rates plus spindle speed, which again determines surface roughness/smoothness. The tool contour can also be selected (e.g. for a screw-cutting machine). For more complex contours the feed rates can be functions of time. Turning machines (lathes) can produce any shape with a cylindrical symmetry.

A typical drilling operation would require 5 parameters: an X-Y coordinate, a depth and radius of the hole, and a surface roughness/smoothness parameter related to spindle speed and feed rate. The hole radius is, of course, the drill radius which is an attribute of the tool. Boring, broaching and honing machines produce successively more precise and smooth interior cylindrical surfaces, but 5 parameters would suffice for each. Tapping and threading machines are specialized to generating interior threaded surfaces. The thread contour is determined by the choice of die, in the case of a tap, and by the tool contour in the case of the threading machine. Saws, shears, planing, lapping and polishing machines all produce successively more precise and smoother flat surfaces (4 parameters). Shaping machines produce grooves in flat surfaces,

[1] A reviewer has noted that this approach could also be applied to the information content of input materials themselves, which constitute an increasingly important component of total costs. Composition and micro-structure can also be considered to be forms of embodied information. This is one of the "hotter" areas of research and innovation today. For a more detailed discussion of some methods of estimating compositional and micro-structural information, see also [1].

with the contour of the groove determined by the tool contour. Gearcutting machines, by definition, produce gear-shapes (7 parameters, not including the tooth contour). Again, the tooth contour is typically determined by the cutting tool.

Assuming the number of control parameters indicated above, the information embodied in products by each machine can be estimated from the maximum feasible number of operations per unit time in a given type of manufacturing (custom, small batch, large batch, or mass production) and the average utilization rate of the machine. This would enable us to construct a general measure of the pace of technological change as reflected in manufactured products.

CIM WITHIN MANUFACTURING

So far we have been considering discrete-part manufacturing as a whole, from a very high level perspective. The next step (from the top down) is to consider the role of CIM within the larger context. Broadly speaking, I have elsewhere characterized CIM technology as the application of computers and micro-electronics to supplement, and partly replace, low level human decision-making in manufacturing.[2] In general, this paper focuses on the metal-working or "engineering" industries (corresponding roughly to SIC 34–37, plus elements of SIC 33 and 38). Even restricting ourselves to the metalworking sectors, an enormous range of products must be considered, together with a wide variety of manufacturing methods and processes.

The choice of technology for manufacturing involves several dimensions, as sketched schematically in Figs. 3–6. The dimension of complexity has already been noted. It applies not only to discrete parts, but to assemblies and complete products. Parts range in complexity from commodity items (such as ball-bearings, screws, bolts and nuts, washers, nails and bottle-caps) to crankshafts, engine blocks and turbine blades. The former are produced by automatic machines in standard sizes, by many competing specialist manufacturers at very low unit cost.[3] The latter are uniquely designed for specific products of individual firms.

Complete assemblies, of course, can be as complex as space-craft and ships. As noted above, the cost of defects depends strongly on the nature of the part and its role in the completed product. The boundaries of the various regions in Figs. 3–6 are not, of course, well defined. Nevertheless, it is clear that they have been shifting gradually over the last two decades as programmable technologies have become more cost-effective. By contrast, the regions appropriate for manually operated or automatic machines have shrunk considerably. This is shown especially in Fig. 6.

Another dimension of the choice problem is precision. Again, there is a considerable range, depending on circumstances. Stand-alone parts like washers and nails need not be very precise in most cases. Indeed frames and housings do not have to be very precise, except where they are in contact with moving parts. On the other hand, axles, sleeves, pistons, ball-bearings, piston rings, gears, turbine wheels and valves must mate very precisely with other parts. Any surface irregularities or lack of precision will result in wear. Wear can lead to failure. The importance of tightly fitting piston rings is obvious. Worn rings permit loss of compression and, worse, loss of lubricating oil, which increases the rate of wear.

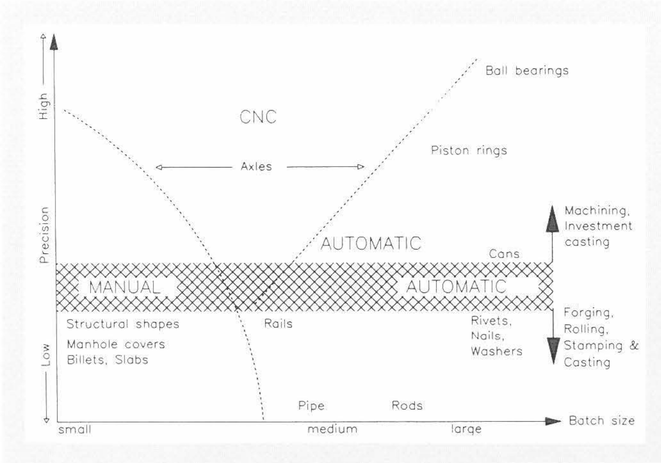

Fig. 3. Low Complexity Shapes

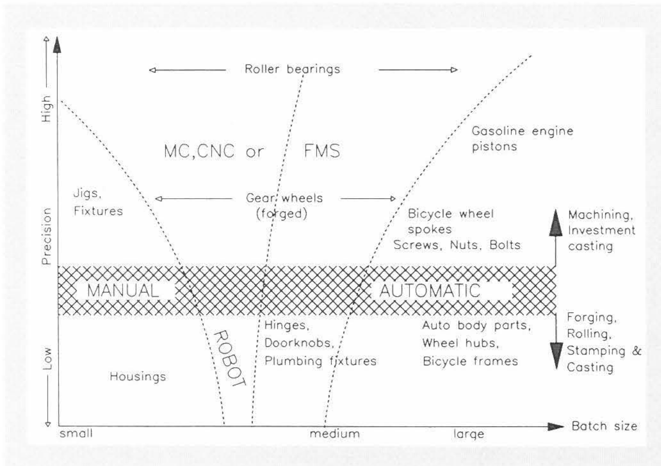

Fig. 4. Moderately Complex Shapes

Gears offer a subtler example of why precision matters: gear teeth normally have an involute curvature with the property that the teeth of linked gears roll without sliding (i.e. without friction) as they turn. As long as the gear teeth retain this ideal curvature, they do not wear. However the onset of wear, such as from tiny bits of grit or metal chips, soon results in sliding, which increases the rate of wear and eventually causes vibration, metal-fatigue, and failure. Clearly, the more precisely gear-teeth can be machined, the longer they will last. As a general rule, metal parts that move against (or with) other parts require a higher standard of precision in manufacturing than non–moving parts. The faster the motion, the greater the need for precision. For high speed rotating machinery, even microscopic dimensional irregularities are quickly translated into unbalanced loads that lead to vibration and wear. (Anybody who has seen a clothes dryer with an un-

[3]It is pertinent to note that the number of such commodity products has increased over time. The availability of such products—especially low-cost connectors—affects the design of manufactured products that utilize them. In many cases, their low cost induces designers to use more of them than might otherwise be the case, thus distorting the overall design of many engineering designs in the direction of greater complexity. I am indebted to a reviewer for pointing this out.

[2]This is the basic perspective adopted for the IIASA *CIM Project*, which began in 1986 and will continue through 1990. The author is co-principal investigator.

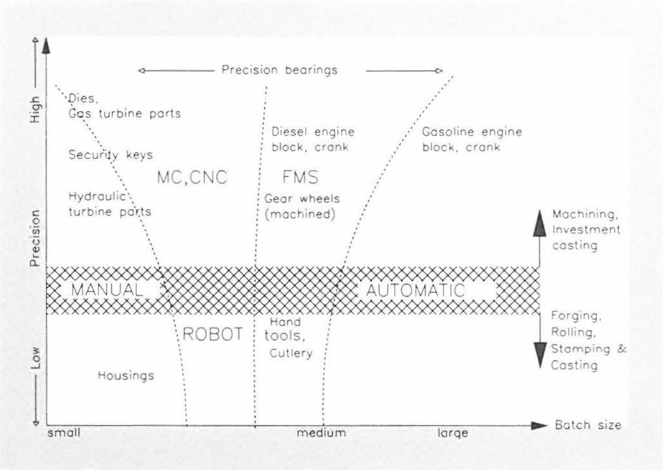

Fig. 5. Very Complex Shapes

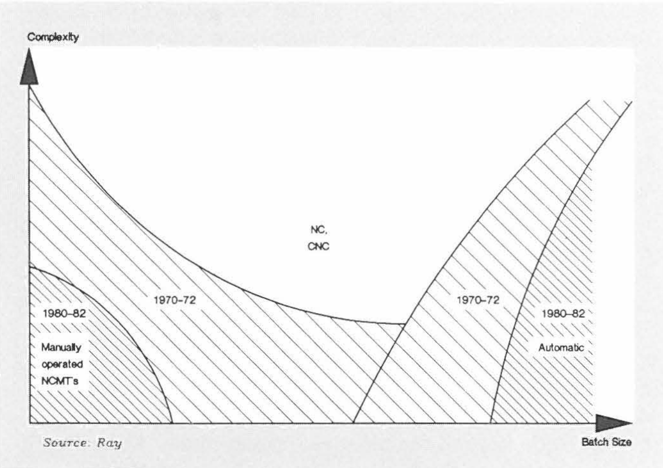

Fig. 6. Complexity—Batch Size

balanced load "walk" across the floor can imagine the problem). Thus, very high speed rotating machinery, such as gas turbines and centrifuges, constitute the most challenging of all manufacturing problems.

Closely related to precision is the control of variance.[4] Manufacturers in the 1990s can be expected to demand significantly tighter control over the width of the band of allowed variance in order to increase overall output quality and reduce re-work. This is one of the primary strategies to reduce the cost of garbage information, noted earlier.

The other major factors involved in the choice of manufacturing technology are materials, physical size, and scale of production. Needless to say, the problems of manufacturing things from glass, ceramics, stone, plastics, wood, paper or textiles are quite different in many respects from the problems associated with metal-working. Even among metals there are great differences between the problems of cutting, shaping and forming soft or malleable metals such as copper vis a vis hard metals such as tool steel or superalloys. For the present, if not necessarily for the indefinite future, the major structural metal is carbon steel, with gray (cast) iron, stainless steel, aluminum alloys and other alloys following in rough order of importance. I shall not, in general, discuss processes used only for special materials (such as the investment casting process used for superalloys).

Size is an important factor in its own right, at least on the micro end of the spectrum, because very small parts cannot readily be handled by human fingers or even discerned by human eyes. Thus increasingly specialized techniques have had to be developed over the decades to manufacture watches (for instance) efficiently. It is probably no accident that a large-scale Japanese watchmaker (Seiko) pioneered in robotic assembly. At the other end of the spectrum, large or heavy workpieces are a special problem because they cannot be easily manipulated by unaided human arms and hands. There is a tradeoff, which applies to machines as well as humans, between dexterity and strength [4]. Very large pieces must be moved and assembled with the aid of massive and correspondingly crude cranes or hoists. For this reason assembly merges with construction.

The other choice factor, as noted, is scale of production. Unfortunately, scale has several possible meanings. In the case of mass production, the relevant measure is just the length of the production run, or the number of pieces over which the capital equipment must be amortized. However, as soon as some capital sharing becomes possible (economies of scope) there are several, perhaps many, joint products. One of the relevant variables is batch size, because each batch is preceded by a setup which takes anywhere from a few minutes to a couple of days, depending on the product and the equipment design. Another relevant variable is the number of different members of the product family that can be made on the equipment. Still another is the frequency of change. All of these are obviously related. In practice, we must consider situations ranging from very large batches (long runs) of a few variants of the same basic design, to customized production of many different parts made once and only once.

The cost-reduction potential of computerized control technologies varies with the type of manufacturing. There is no impact in situations where there is no variation either of the product or the production level. This might apply, for instance, to fully automatic production of completely standardized products such as nuts and bolts, sparkplugs, or lightbulbs. On the other end of the spectrum, there is also little or no impact in situations where the product is always different and made to measure, as in some tool and die or industrial pattern shops or machine shops building experimental design prototypes. This domain may be accessible in the future, however, to truly intelligent machines. (The nature and degree of intelligence needed will be discussed later).

However, most production lies between these extremes. Starting from the low volume job shop level, a reasonable amount of design work might well justify at least a small micro-computer based CAD system to simplify design changes and record-keeping. With a still larger volume of business, especially in the area of high precision and complexity, a stand-alone NC milling machine or lathe (or two) might make sense to reduce machining time and increase accuracy. For higher volumes still, machining-centers with CNC controls

[4]Lack of control over variance, rather than precision per se was the barrier to interchangeability of parts, which was first recognized and addressed historically in the manufacture of small arms. For a good discussion of how this problem influenced the evolution of manufacturing, see, for example, Hounshell [Hounshell 84].

and automatic tool–changing capability begin to make economic sense for complex parts.

The next step, as one moves up the volume scale, is to divide the sequence of operations among several more specialized machines. At first this might involve control of the individual machines from a single mini-computer which downloads the instructions for each part to each machine in the sequence required. Loading and unloading and transfer can still be manual. Of course various degrees of automation can be applied to the material-handling problem, from simple roller or belt conveyors to automatic transfer machines, automatic guided vehicles (AGV's) or robots with special-purpose grippers. A technology that is not yet available, but which is gradually being developed, is the general purpose gripper [4]. When a number of machines is linked together and run by a common computer, the system is called a flexible manufacturing system or FMS.

As it happens, the FMS solution can also be reached, as it were, by evolution from the mass production end of the spectrum, by adding some flexibility to a conventional hard automation system. In point of fact, the realm of batch production is beginning to subdivide into distinct sub-regions, depending on the volume-variety tradeoff. This tradeoff is illustrated in Fig. 7. In effect, two kinds of FMS systems appear to exist, namely small systems, which are designed for small batch production with considerable variability and cost less than $5 million, and large systems which are designed for large batch production and much less product variation, and which cost closer to $20 million [5]. The first category utilizes a minicomputer for scheduling and downloading operating programs to individual machines, but most setups, loading and unloading, and inspection is manual. The second category of system does not necessarily have more machine-tools than the first, but the machines are designed for long life and high production rates with minimum human supervision. Loading and unloading, parts transfer, storage and inspection are likely to be automated. The software systems required to control the associated materials handling and inspection functions tend to be correspondingly more elaborate and expensive.

Another type of large system, also quite expensive, is designed not for large volumes but for very large part families (in the thousands). In such cases, the software is even more elaborate and may become a substantial fraction (half, or more) of the total investment costs. Several of these systems have been installed by aircraft manufacturers, such as General Dynamics, Vought, British Aerospace (U.K.), and M-B-B (West Germany). Machine tool companies have also built a number of such systems for their own use. Examples include Fanuc and Yamazaki in Japan, and Cincinnati Milacron and Ingersoll Milling Machine Co. in the U.S.

The $20 million Ingersoll system, for instance, has been under development for more than a decade [6]. It was originally planned to manufacture 25,000 different parts annually, of which 70% were in lots of one, and 50% would be unique and never repeated (it is doubtful that this ambitious goal has yet been fully achieved). It consists of 3 cells which replace 40 stand-alone machine tools. The system links order entry, production scheduling, bill-of-materials, geometric modelling and billing. This involves an integrated, company-wide computerized management and business information system (MIS/BIS). This task alone involved replacing 1300 applications programs and 225 separate files, and took 2 years to complete. It is too early to judge whether the Ingersoll system, or others of comparable scope and cost, are going to be successful enough to stimulate many imitators, or whether they will be judged a few years hence as over-ambitious failures.

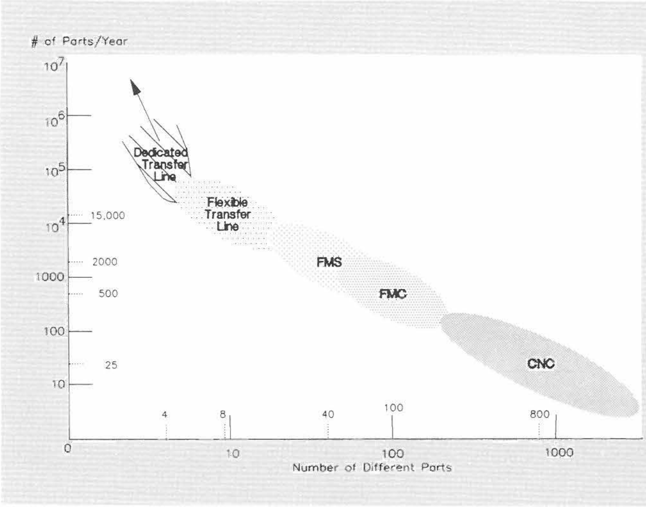

Fig. 7. Volume/Variety Tradeoff

WHEN WILL MACHINES BE "INTELLIGENT"?

Before proceeding to forecasts of CIM performance, it is worthwhile to review the current status of CIM technology from the perspective of limits, i.e., what it cannot yet accomplish. Given the widespread use of terms like *intelligent robots* and *expert systems,* not to mention the rather optimistic specifications of some of the advanced systems recently built or currently planned, it is not unreasonable to wonder why CIM technology is not being adopted faster than it is? The plain fact is that in the realm of eye-hand coordination and decision-making, machines are not yet able to substitute for human skills beyond the most elementary ones. According to two researchers at the leading edge in the application of artificial intelligence to manufacturing technology:

> In the global view of the world . . . represented in glossy trade magazines, the machine level of the factory hierarchy is normally represented as a black box with its own controller. From a senior management point of view, there might be the temptation to believe that the machine tool is already an unattended autonomous unit. However, more day-to-day experiences with machine tools quickly show that this is not the case . . . [4].

The authors go on to point out that, while there are some examples of NC machine tools being run unattended for batch production (such as the Fanuc plant at Fuji, Japan), this is currently possible only in very restricted conditions. For example, part accuracies cannot be held to less than 0.002 inches, programs must be debugged and run many times under manned conditions before being run in unmanned conditions, part geometries involving critical cutting conditions are avoided; feeds and speeds are set very conservatively to make cutting as predictable as possible, fixtures, tooling and magazining are all done manually before hand, etc. Putting it another way, "the production of a good part that is right the first time in a rapid prototyping environment is extremely difficult. The full automation of such a process in which only a handful of parts are to be made is currently impossible" [4].

When newly designed parts first go into production, there is always a learning curve. As a general rule, the first few parts are carefully compared with the desired standard. Deviations require adjustments to be made to the programs, the tools and the fixtures. In a typical case, there is still a 20% probability of an out of tolerance defect in parts numbered 6–15, and a 10% probability in parts numbered 16–25 [Kegg, cited in 4]. Most of the problems that arise here are resolved on the spot by a skilled machinist. The principal source of defects (as might be expected, in view of what was said earlier) is human errors in programming or setting up the NC tools. The errors only show up when the tools are actually operated, and then the problems must be diagnosed and fixed based by the expert machinist.

What are the types of knowledge involved, and how long does it take to acquire? As to the first question, Wright & Bourne [4] list the subsystems that will surround the central processing unit (CPU), or cortex, of the future intelligent machine-tool controller (the black box in the standard hierarchical control diagram), along with the estimated CPU usage of each subsystem:

CAD description (5%)
Operator interface (7.5%)
Plan formation (12.5%)
Machine tool control (12.5%)
Robot control (10%)
Fixture lab (5%)
Gripper lab (5%)
Tool supply (2.5%)
Stock supply (2.5%)
Chip removal (2.5%)
Sensor lab (5%)
Unified interpretation (7.5%)
Inspection (10%)
Vision monitoring (12.5%)

Even a top-of-the-line machine controller of today lacks most of these functions. Since programmable grippers and fixtures (hands) do not yet exist on commercial machines no cortex functions are yet allocated to them. Similarly, vision systems have not yet been integrated with machine tools. Finally, existing systems have no ability to plan or make decisions, so these cortex functions are also lacking at present. Moreover, the operator interface is currently very clumsy and inefficient, since the machine cannot hear, interpret, or reply to spoken commands.

When, if ever, will machine tools become intelligent enough to dispense with a skilled machinist in the debugging mode described above? Sensory feedback—primarily vision and taction (from the flexible grippers and fixtures)—is a prerequisite [7]. But the ability to correctly interpret visual and tactile information in terms of internal models of the machine and its appendages, the workpiece, and the cutting tools is the essential missing ingredient.

Wright & Bourne see significant progress over the next 20 years, with unattended machines capable of error recovery diagnostics by 2010 [4 p. 290]. In view of a history of over-optimistic forecasts in the field of artificial intelligence (AI), it would not be surprising if the suggested 20 year time-frame also turns out to be too short.

It is not appropriate here to summarize the content of the machinists skills or other manufacturing skills that need to be captured. For the most part they are concerned with choosing sequences of operations, setting feed rates and cutting speeds and avoiding trouble. Trouble can arise from a variety of sources, such as vibration, excessive tool wear, heating, jamming, accumulation of chips and shavings, etc. Problems cannot always be anticipated, especially in cases where it is necessary to operate near the margins of capability (as in dealing with very hard metals, or metals extremely subject to work-hardening. The machinist, relying on years of experience, relies on a variety of signals, ranging from the color and length of the chips to the sound of the cutter and even the smell of the hot oil. He interprets the data and modifies the settings on-line if possible; or he stops the machine and changes the fixtures or the program. He occasionally diagnoses incorrectly and makes the wrong decision, which must be corrected later. Incorrect diagnosis is the inevitable consequence of uncertainty. The human machinist learns from his mistakes and becomes more skilled as time goes on, but he can never hope to avoid all errors.

In this context, it is relevant to note that the higher levels of human skill in this field (like others) requires many years of study and effort to achieve. Given that computers are still unable to beat the best human chess players—despite an intensive effort spanning decades—it is really not plausible to imagine that intelligent machine tools will supplant skilled machinists in a shorter time. Progress in computer hardware can be assumed, but hardware is not the problem. The difficulty in the case of chess is that even the best and most analytic chess players are unable to describe how they evaluate positions and choose among possible moves in a way that can be reproduced by a computer.

Yet the rules of the game of chess are relatively simple and explicit and there are no uncertainties to contend with, except the intentions of the other player. In the case of machining (or other manufacturing processes) the rules and constraints are far more complex. Moreover, they vary from case to case, depending on the material, geometry and precision desired. Finally, there are significant inherent uncertainties to contend with. (For example, tools from the same batch may differ in useful life by a factor of 4). Moreover, skilled machinists are not likely to be good at articulating and analyzing their own thought processes. Thus, although a start has now been made at codifying this kind of knowledge in expert systems, the level of expertise that can be embodied in such a system is not likely to be really effective for many years to come.

In fact, the most rapid progress in automating small batch production is likely to come from a completely different source, namely computer-aided-design. Until very recently, designers typically had one objective, namely to maximize the functionality of the product. Manufacturability was a constraint, of course, but design changes to make a part easier to produce were usually afterthoughts resulting from wrestling with actual difficulties in the shop. In recent years, efforts have been focussed in several laboratories on codifying principles of design for manufacturability, especially assembly [8, 9]. Dramatic savings in production costs have been demonstrated in a number of cases by simplifying and rationalizing the design. It is likely that designers in the future aided by intelligent CAD systems, will be increasingly able to avoid calling for combinations of part geometries, tolerances and materials that create difficulties and uncertainties for machinists. This is, in fact, by far the most promising route to the goal of a good part the first time.

MEASURES OF TECHNOLOGY

Intelligence apart, a list of the important attributes potentially distinguishing CIM from conventional manufacturing technologies is a good starting point. The following have been suggested:

1. Ratio of unmanned/manned time for machines or cells
2. Maximum continuous unmanned time in practice
3. Fraction of unproductive machine time
4. Workpiece cycle (throughput) time
5. Work-in-progress/output ratio
6. Order-to-delivery time
7. Reject fraction
8. Product variety (family size)
9. Average batch size
10. Direct/Indirect labor ratio
11. Software fraction in invested capital

Bearing in mind the issues noted in the previous section above, one of the best surrogate measures of the level of CIM technology is probably the fraction of software cost to total manufacturing system cost, or the fraction of software in capital investment. It can be argued that this is a rather direct measure of flexibility, since software-driven systems are presumably reprogrammable, in contrast at least to hard automation. A schematic tradeoff curve showing the increase of software costs relative to span of control is given in Fig. 8.

Some confirmation of the figures in Fig. 8 can be found in the data we have gathered so far. Stand-alone Numerically Controlled Machine Toll (NCMT) costs, today, are roughly 1/3 attributable to operating software [10]. When a number of NCMT's are linked together in an FMS, the NCMT's account for 50–55% of total costs, (of which software accounts for a third, as noted) and systems control, communications and interfacing software adds another 20–30% or 37% to 48% in all [10–12]. These figures seem to be fairly stable for both small and large FMS's. Software is said to account for 50% of the cost of one recent showcase Japanese automated factory, and may reach 60% for the massive effort currently under way at General Motors. (This was the reason GM spent $2.6 billion to acquire Electronic Data Systems Inc. a few years ago).

For a fully computer-integrated factory of the future with all major functions assisted or carried out by computers linked to centralized, company-wide databases, the software fraction of total investment may well reach the 80% level already characteristic of large military systems. The projected growing fraction of software investments vis a vis hardware investments over time is shown in Fig. 9.

Several of the other attributes listed above also reflect aspects of flexibility, of course. For instance, a high degree of flexibility corresponds to the smallest possible order-to-delivery time, the smallest possible inventory of work-in-progress, and the maximum ratio of product variety to batch size. These data may be available for scattered cases, perhaps with some before and after comparisons, but industry-wide data are not available. The same holds for reject rates (a quality indicator) and tolerances. In fact, it is not clear that CIM will have any impact either way on the latter.

Another kind of technology measure is suggested by the foregoing discussion of manufacturing in terms of machines embodying information in materials, one discrete operation at a time. The time required for each operation is a function of the rate of cutting or forming. This has been increasing rapidly for a century or more (Fig. 10), but it is not clear that past rates of improvement can be sustained. The reason is that improvements have mostly resulted from the development of harder cutting materials—from tungsten steel to nitride and boride ceramic coatings. The latter approach the hardness of diamond, which is the hardest known material. Diamond coated cutting tools from Asahi Diamond Industrial Co (Japan) reached the market-place early in 1988 [N.Y. Times 10/25/88]. At least one expert has remarked that cutting technology has already reached 90% of its theoretical maximum potential [13].

On the other hand, the utilization of the available time of cutting tools is still quite low, on the average. Data for the U.S. were compiled by the Machine Tool Task Force [14]. A summary of the time budget for U.S. machine tools in small batch, large batch and mass production is shown in Fig. 11. One of the major savings offered by NC is to increase the utilization rate of expensive capital equipment. This can be regarded as an indicator of *system efficiency*.

There is indirect evidence (statistics are lacking) that stand-alone NCMT machines are utilized between 2 and 3 times as efficiently as conventional manually operated machines. One early study in Germany concluded that one NC

Software Fraction of Total Investment	Span of Computer Control	Added to Prior Level
0.02	Stand–alone Machine	Instructions for machine control
0.03	Machining Center	Instructions for changing tools
0.04	Maching Cell	Multiple machine control
0.06	FMS(1)	Scheduling
0.10	FMS(2)	Loading/Unloading, Storage
0.15	FMS(3)	Inspection, Sorting
0.20	Automated Production Line	Assembly, Palletizing, Kitting
0.40	Automated Factory(1)	Computerization of Functional Modules viz. MIS, MRP, CAD, CAPP, CAM
0.50	Automated Factory(2)	Linkage of MIS, MRP, Order Processing, Scheduling, Cost Analysis
0.70	Automated Factory(3)	Linkage of CAD, CAE, CAPP & CAM

Fig. 8.

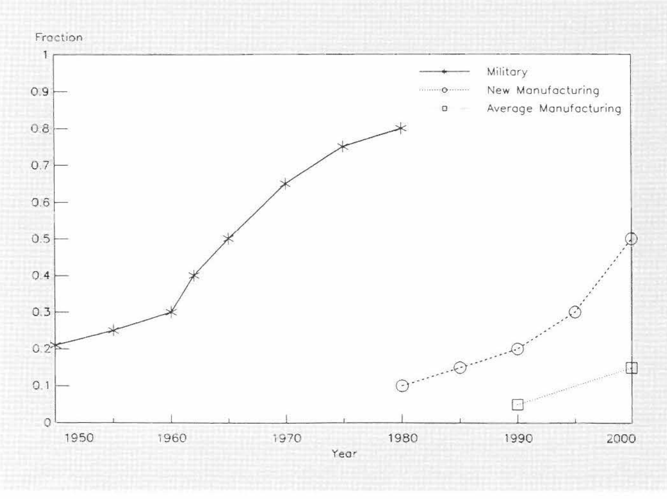

Fig. 9. Software as Fraction of Total Capital Investment

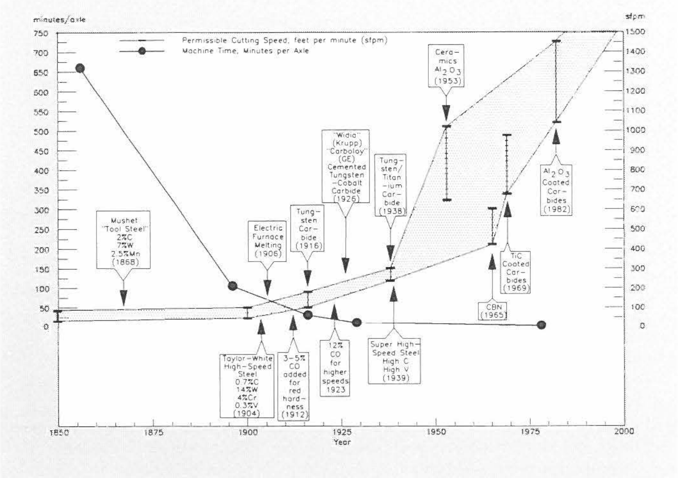

Fig. 10. Machining Speeds For Steel Axle Machining Time & Permissible Cutting Speed

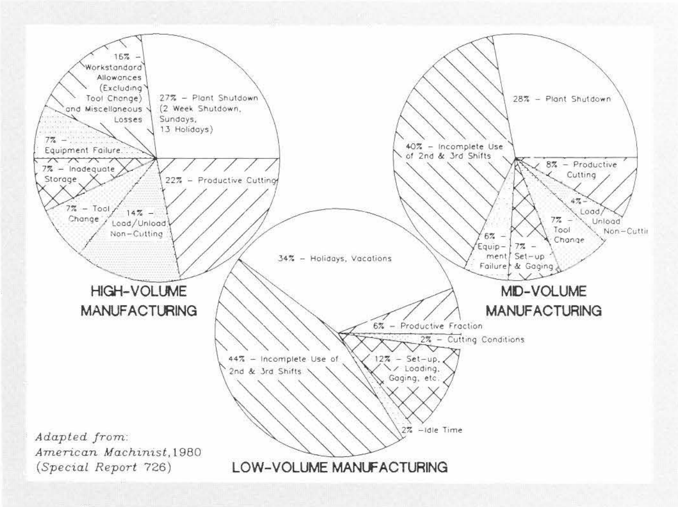

Fig. 11.

milling machine displaced 3 conventional drillng machines one NC milling machine displaces 2–3 conventional milling machines, and that one NC machining center displaces 2 drills, 1 milling machine and 1 boring machine [15]. Similar substitution ratios appear to be applicable to recent FMS installations. Since NC machines operate no faster than conventional machines, all of the increased output can be attributed to more efficient use of working time, especially faster setups. In short, unproductive time is sharply reduced.

When the NC machines are linked by programmable materials handling equipment and controlled by a central computer to manufacture a family of parts with closely related designs (in an FMS), the machine utilization rate tends to be significantly higher still. In part, this can be explained as a reduction in scheduled idle time, a straightforward economic response to the increased cost of capital equipment. But the utilization rate of machine tools is also a useful measure of the capability of CIM. A schematic illustration of the trend is shown in Fig. 12. Regrettably, there are very few published data that would permit reliable quantification of this trend on an aggregate level.

Still another surrogate measure of integration could be the percentage of NCMT's that are not stand-alone but controlled by higher-level computers (Digital Numerical Control or DNC) and especially those that are linked together by programmable materials handling systems in cells or FMS. In this context, it is noteworthy that a Delphi forecast carried out in 1977–78 by the Society of Manufacturing Engineers (SME) of the U.S. predicted that by 1987 the fraction of new machine tools sold for FMS or similar uses would reach 15%, rising to 50% by 1990 [16]. Recent data for Finland confirm this forecast: current annual sales of NCMT's are around 300 units, of which 60 (20%) are associated with FMS's; of the installed machines, 150 out of a total of 1600 NCMT's in Finland are associated with FMS's [10]. A study by the Commission of the European Communities estimated recently that 40% of all current NCMT investments are associated with manufacturing cells or FMS's in the main industrialized countries [17]. A recent market study cited by *FMS Magazine* (April 1987) projects that by 1997 up to 70% of all U.S. machine tools will be operating in 'cells' or FMS, with an overall increase of 5-fold in efficiency. Apparently the actual pace of change is now somewhat ahead of the SME forecast.

The most direct of all measures of CIM penetration would be the percentage of manufacturing operations (including assembly) that are automated i.e. carried out under computer control without direct intervention by human workers. Again lack of reliable data will make it hard to quantify. As usual, data will be scattered and difficult to extrapolate beyond particular cases.

One last measure worth considering briefly is the ratio of direct (hourly paid) to indirect labor. This is roughly related to the degree of "hands on" labor as compared to supervisory and other functions carried out by humans. However, the relationship is only approximate and the definition of direct labor depends very much on traditions in particular industries, union contract language and other institutional factors. This topic might repay more intensive research, but such a ratio could not be used bare (without considerable explanation and interpretation), even if the data were readily available.

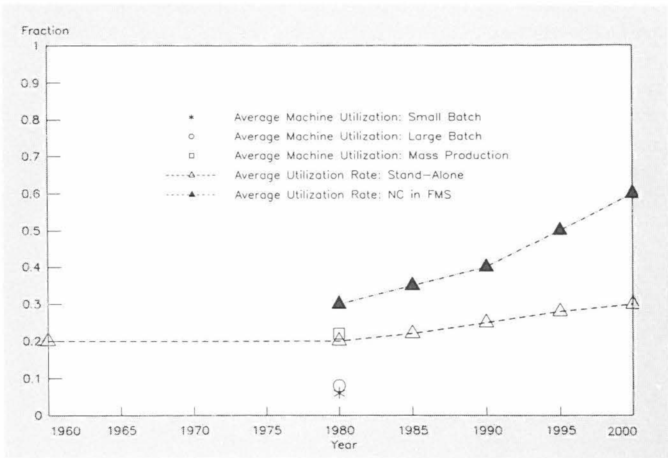

Fig. 12. The Impact of Computer Control on Machine Utilization

In regard to all of the above measures, it must be emphasized again that they are hybrids, reflecting elements of both pure technological performance and market penetration. This seems to be unavoidable.

CONCLUSIONS

The projections displayed already in Figs. 8, 9, 12 can be regarded as forecasts. Together they present a picture of the future of CIM technology from a fairly high level perspective, as promised at the start. However, some important topics have not yet been addressed in specific terms. In this section we will attempt to fill some of these gaps. We also address the important issue of "push" vs "pull." In the latter context it is also important to not the existence of drag effects, or bottlenecks. Of these, the greatest is the difficulty of capturing human manufacturing skills in intelligent machine controllers.

One topic that has been neglected thus far is logistics. We have noted that one of the most important expected benefits of CIM is a reduction in order-to-delivery time. This will result, in part, in a reduction of actual manufacturing cycle time. Its real benefit, however, is to make possible a dramatic reduction in inventories, which represent idle capital, and to serve customers better.

There are two distinct aspects to this problem representing two different situations. The first concerns standard products. At present, when a customer orders an existing standard product it must be taken from an inventory of finished goods ("off the shelf"), most likely sitting in a warehouse in the wholesale trade sector.

The second situation has two subcases. If the product is an existing one it must be ordered from the factory where it must await the next batch of that particular item, or it must be treated as a special order (batch-size of one) and jump to the head of the queue. In the absence of flexible manufacturing technologies, special-ordering of spare parts (e.g. steam turbine blades) is a very expensive procedure, since the routine of the entire production facility is interrupted, and no economies of scale can be realized. Yet, in the case of spare parts for major items of capital equipment, like steam turbines, these high costs are still preferable to the opportunity costs of idle generators. In fact, there are quite a lot of examples where a spare part must be produced as fast as possible, at almost any cost, to keep a large system operating. Spare parts inventories ameliorate the problem, to a degree, but in some cases there is simply no possibility of having a spare available on site for every part that might fail. Thus, the potential benefits of a quantum leap forward in flexibility are unquestionably very large. From this point of view alone, there is ample economic justification for the large investments that are now being made in CIM technology. MR

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