WORKING PAPER

FUTURE TRENDS IN FACTORY AUTOMATION

Robert U. Ayres

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IIASA
International Institute
for Applied Systems Analysis

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
A-2361 Laxenburg, Austria

FOREWORD

This paper is a review of contemporary manufacturing technology, from both a U.S. and world perspective. It emphasizes the historical background 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". Prof. Ayres believes that the next industrial revolution is a fundamental shift from the use of human workers as "micro" decision-making (machine controllers) in factors to the use of "smart sensors" for this purpose.

The paper elaborates some of the more specific implications.

Thomas H. Lee
Program Leader
Technology, Economy, Society

Author's Preface

A shorter version of this paper was originally prepared in Summer 1986 for the Commission on Technology and Employment (US National Academy of Sciences/National Research Council). However, the subject is so closely related to the CIM project that it seems worthwhile to add more material and make it available, prior to eventual publication in the Commission report, to others interested in the topic, especially members of the CIM network of collaborating institutions.

Robert U. Ayres

Acknowledgement

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 PhD 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 PhD under Steve Miller's direction.

Sources of Past Gains in Manufacturing Productivity

The direction and pace of change in any technology can only be forecast on the basis of a solid grasp of the historical background. If the changes now apparent in the field of manufacturing technology are truly portents of a second (or third) industrial revolution, as some have argued, then it is not inappropriate to look back, at least briefly, at the changes that have taken place since the first industrial revolution, in the late 18th century.

The best known innovation of the first industrial revolution (c. 1770-1830) was the substitution of steam power for water power and animal muscle power. This was of great importance in England, where good sites for water power were scarce to begin with and were essentially exhausted by the end of the 18th century. Horses, too, were expensive to maintain because of the high price of feed. However, in the U.S., where animal feed was plentiful and water power was more readily available, steam power was introduced initially only for river and then for rail transport. The economic benefits of steam power (vs. water power), even in the U.K. were quite modest--of the order of 0.1% p.a. added to the annual growth of GNP--at least up to the 1830's when railroad-building began in earnest (von Tunzlemann, 1978). Mechanization, the application of mechanical power (from water or steam) to drive textile machinery and wood or metal-working machines, seems to have been for more significant, in the long run. Mechanization made possible enormous increase in manufacturing productivity throughout 19th century (Table 1). However, the application of massive amounts of steam power to a single factory drive shaft peaked in around 1900, as shown in Figure 1, although the total

Table 1

Productivity Increases Due to Mechanization

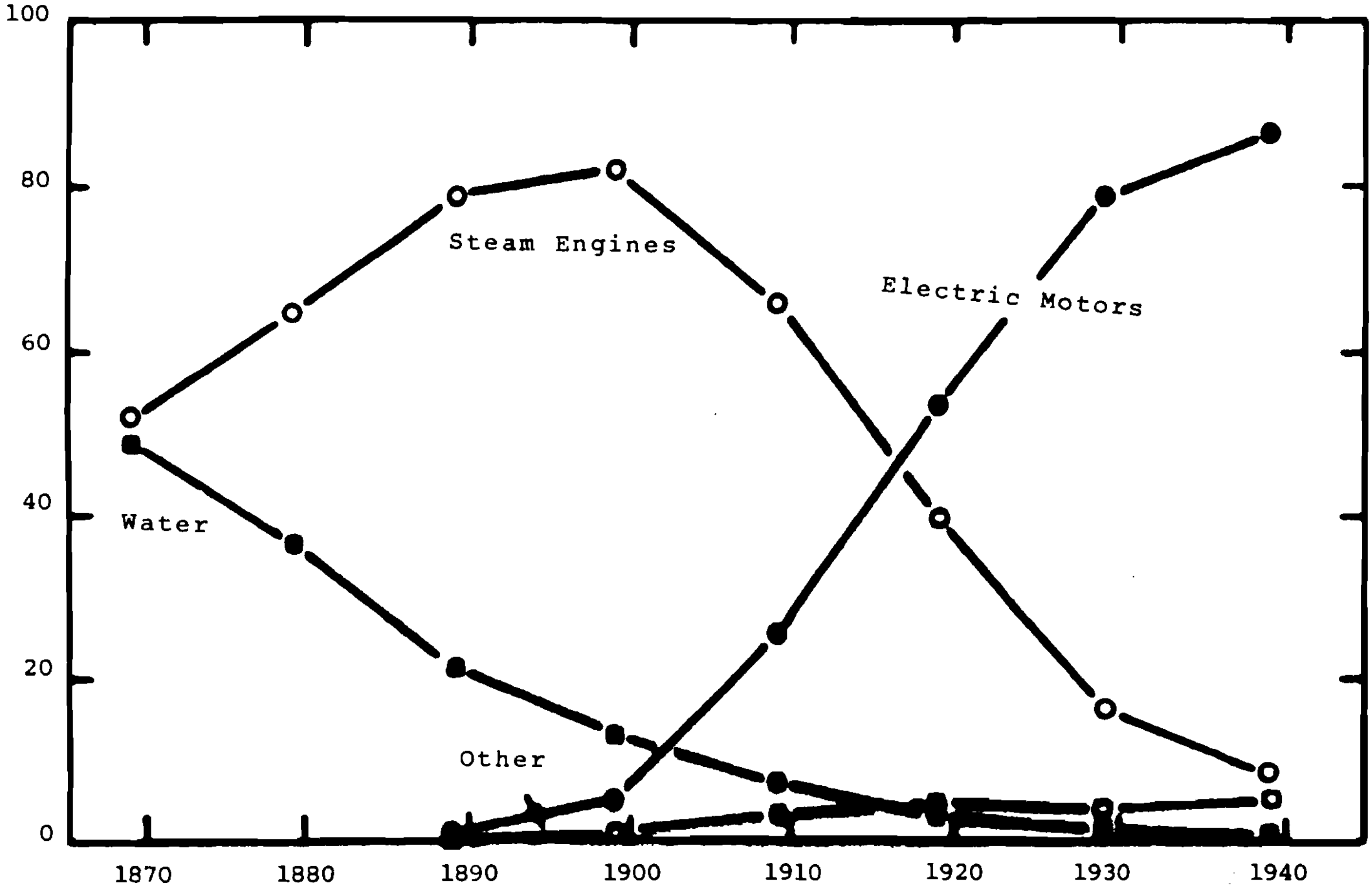
Item	Period	Increased Output per Man-hour (Multiplier)
Metal Products		
pitchforks (steel)	1836-1896	15.6
plows, iron and wood	1836-1896	3.15
rakes, steel	1858-1896	5.96
axle nuts (2")	1850-1895	148
carriage axles	1856-1896	6.23
carriage axles (4" steel)	1862-1896	6.23
tire bolts (1 3/4" x 3/16")	1856-1896	46.9
carriage wheels (3'6")	1860-1895	8.41
clocks, 8-day brass	1850-1896	8.30
watch movements, brass	1850-1896	35.5
shears, 8"	1854-1895	5.51
saw files, 4" tapered	1872-1895	5.51
rifle barrels, 34 1/2"	1856-1896	26.2
welded iron pipe, 4"	1835-1895	17.6
nails, horseshoe, no. 7	1864-1896	23.8
sewing machine needles	1844-1895	6.7
Other Products		
bookbinding, cloth (320 pp)	1862-1895	3.80
mens shoes, cheap	1859-1895	932
womans shoes, cheap	1858-1895	12.8
hat boxes, paperboard	1860-1896	3.22
wood boxes (18" x 16" x 9")	1860-1896	9.73
paving bricks	1830-1896	3.89
buttons, bone	1842-1895	4.04
carpet, Brussels	1850-1895	7.95
overalls, mens	1870-1895	10.1
rope, hemp	1870-1895	9.74
sheet, cotton	1860-1896	106
electrotype plates	1865-1895	2.91
chairs, maple	1845-1897	6.43

Source: R.U. Ayres (1984)
Data from US Department of Labor

Figure 1

Sources of Mechanical Drive in Manufacturing

Establishments, 1869-1939



Source: W.D. Devine, 1982

installed horsepower per unit of output continued to grow at an average rate of 1.1% p.a. from 1899 until around 1920 (Schurr, 1984). It declined thereafter until 1953, and has increased slightly since then. Factory electrification (electric motor machine drives) was highly beneficial in terms of flexibility of operations and plant layout. In fact, the adoption of electrified unit drive appears to be a major factor in the rapid improvement in U.S. productivity growth that occurred after World War II (Schurr, Ibid).

Yet, there were other major contributions to productivity gains since 1800. The most important historical milestone in the history of manufacturing, by some accounts, (e.g. Hounshell, 1984) would be the ability to produce truly interchangeable parts. This had been an explicit goal of mechanical technology since 1717 (France)[1]. Interchangeability was often claimed--for instance by Colt (c. 1850)--but it was not a practical reality until the 1880's. The Elizabeth N.J. plant of the Singer Sewing Machine, Co. was probably the first to achieve this distinction (Ibid). Colt's famous exhibit at the Crystal Palace in London (1851) created a media sensation and undoubtedly marked a significant step in mechanization.[2] It resulted in contracts for Colt to build munitions factories of his design for the British Government. Underlying the achievement of interchangeability was a series of innovations

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[1] Reported by Charles Fitch, who prepared a report on the "American System" for the US Census of 1880. Interchangeability of gun parts is extremely important in field conditions.

[2] Based on data attributed to Sandvik Steel Co. (Coromant Div.) and quoted in <u>American Machinist</u>, 100th Anniversary Issue, 1977, p. 108.

in precision, metal-working, and measurements by Wilkinson, Stowell, North, Whitney, Whitworth and Fitch, and others. The trend towards increased precision in measurement (Figure 2) has continued to the present, and even accelerated since WW II.

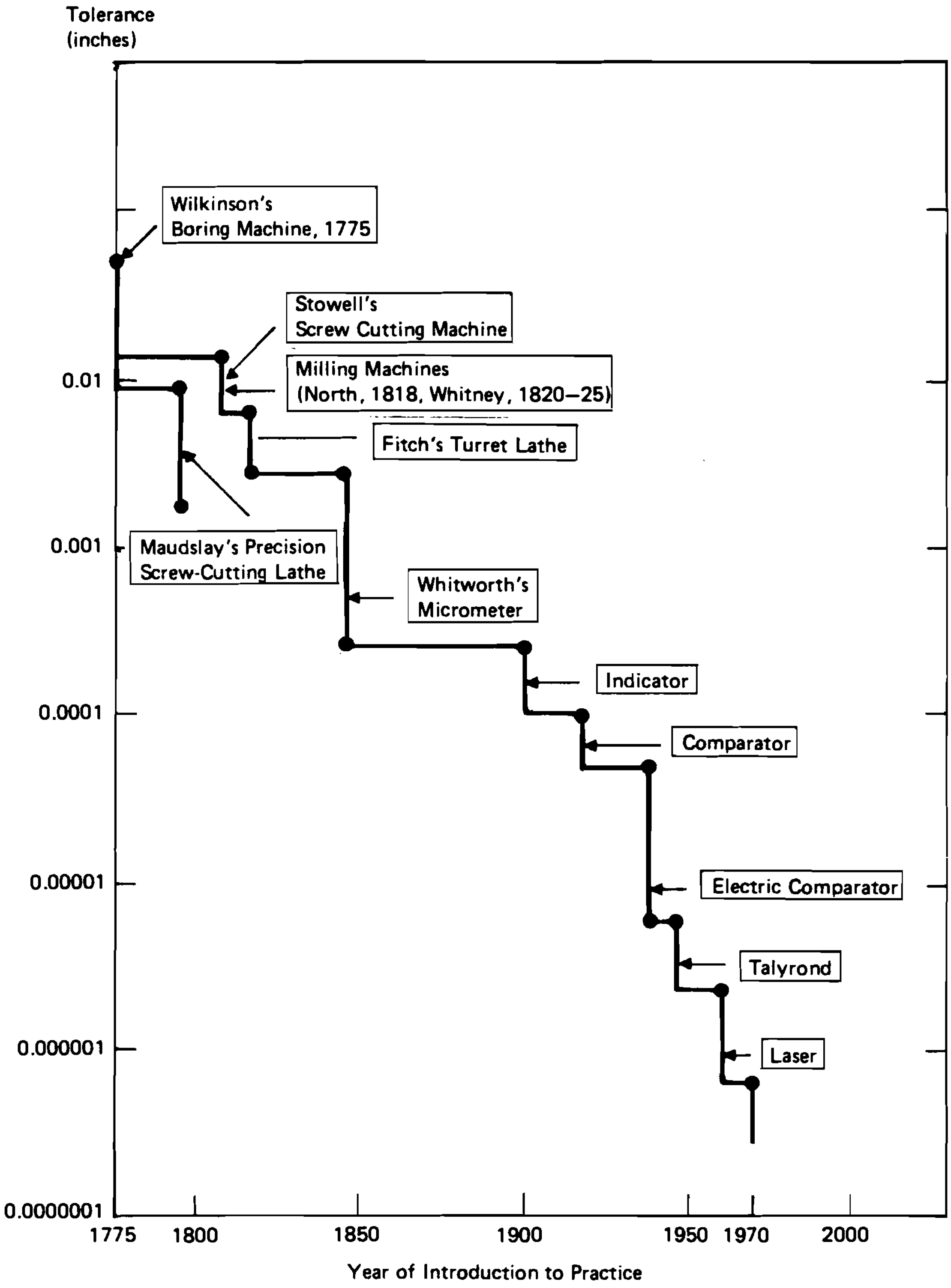
On the other hand, there is little or not evidence of major improvements in machine tool performance since 1900. Modern production machine tools tend to be much bigger and more powerful than earlier counterparts, but they are scarcely more precise. In fact, econometric analysis of data covering many decades by two RAND economists revealed the curious fact that, based on attributes listed in catalogs, machine tool productivity, with characteristics held constant has declined more or less continuously at about 2 percent per year since the 1890's (Alexander & Mitchell, 1985).

Yet, there is equally strong evidence that machine output per labor hour input has increased enormously over the same time. For example, a 36" verrtical boring mill in 1950 operated by 1 man could produce the same output in 1 day that would have required 50 such machines (and 39 operators) in 1890. Similarly, a 20" engine lathe with 1 operator in 1950 produced the same output as 30 machines (and 50 operators) in 1890. Both examples, and others, are given by Tangerman (1949) in American Machinist and cited by Alexander & Mitchell (op. cit.) Similarly, the American Machinist 100th Anniversary issue (1977), cited a theoretical turned part that would have required 105 minutes to machine in 1900, as compared to less than 1 minute in 1975.

The most likely explanation of the Alexander-Mitchell paradox is that harder metals introduced since 1900 permit

FIGURE 2

ACCURACY OF METAL REMOVAL



Source: Author

higher cutting speeds and less frequent tool changing. Prior to the mid-19th century the hardest available metal for cutting was carbon steel made by the crucible process (c. 1740) and "case-hardened" by heat-treatment. A major step forward was the introduction in 1868-1882 of manganese-wolframite-based "self-hardening" alloys by Mushet (Tylecote, 1976). These were the predecessors of "high-speed" tungsten steels developed especially by F.W. Taylor and White (c. 1900), which resulted in something like a 70% increase in the maximum cutting rate from 1900 to 1915. The introduction of cemented tungsten carbide cutting tools resulted in cutting speed increases of the same magnitude between 1915 and 1925.[3] Another major innovation was tungsten-titanium carbide, introduced by McKennon in 1938. Somewhat surprisingly, although few new cutting tool alloys have been introduced since then, tool fabrication (e.g. hardcoating) techniques have resulted in surprising further gains.[4] Maximum cutting rates increased by no less than a factor of 10 from 1925 to 1975 (Figure 3). Interestingly, rapid improvements in cutting technology are still continuing but the most recent gains are primarily due to advances in gas bearing technology that will permit cutting speeds, in principle, at least 10 times greater than 3000 sfpm[5] achieved by off-the-shelf machine tools in 1977. (American Machinist, 1977). Machine tools have, once again, become a dynamic technology.

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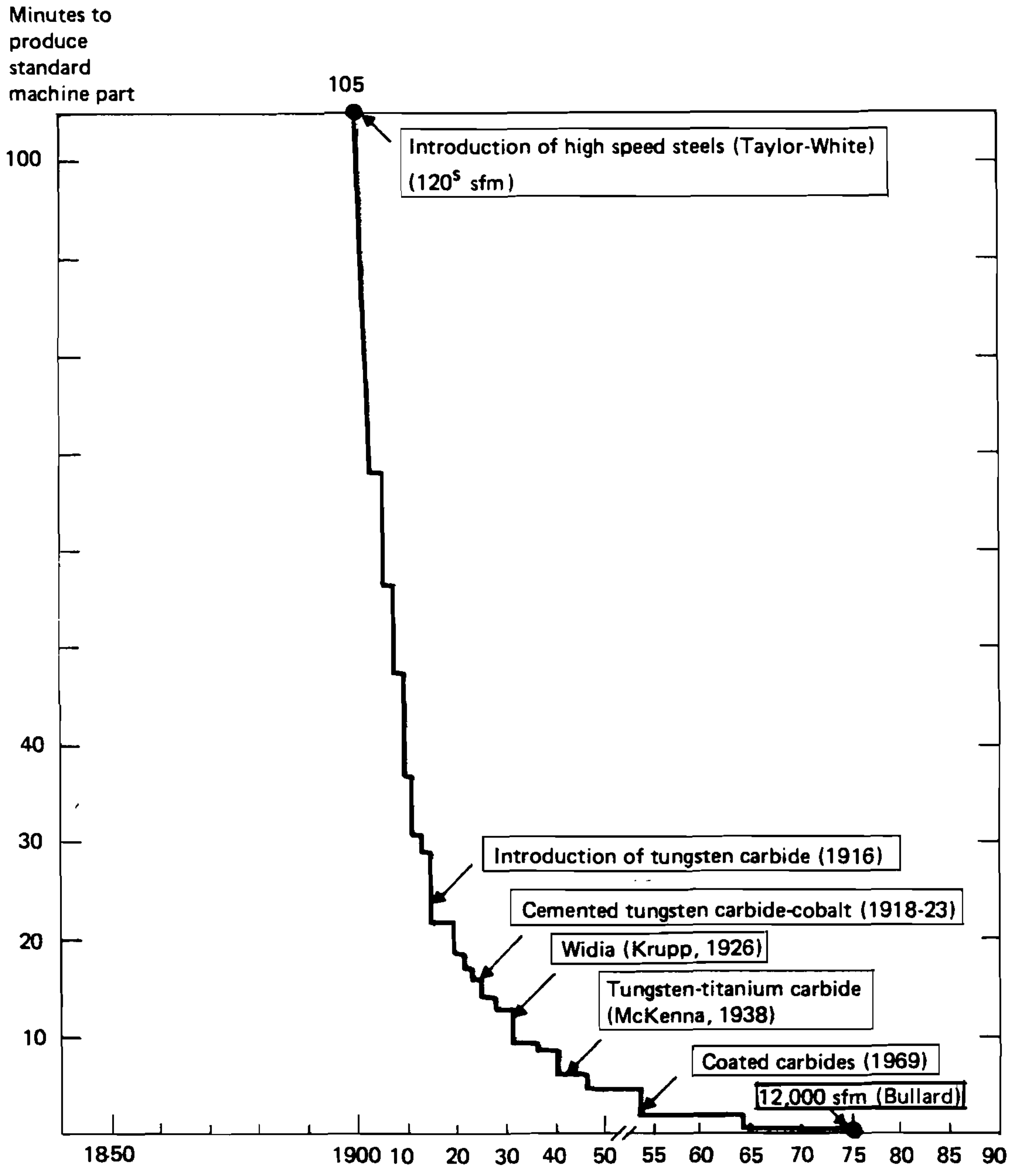
[3] Ibid

[4] Ibid

[5] sfpm = surface feet per minute

Figure 3

MACHINING TIME FOR TURNED PART



Source: Author. Based on data cited in *American Machinist*, Nov. 1977.

Continuing gains in cutting speed have not been matched by comparable improvements in other areas of manufacturing, unfortunately. In the early 19th century, manufacturing labor was predominantly concerned with wood or metal cutting and forming, but by 1900 progress in metal-working together with increased product complexity had changed the nature of the problem. The assembly of a complex product such as a clock, sewing machine, or bicycle--supposedly made from standardized interchangeable parts--typically constituted a labor-intensive activity requiring highly skilled "fitters". This was particularly true in Europe, where the greater availability of skilled labor resulted in a greater emphasis on high quality (better finished) manufactured products as compared to the U.S., where there was a greater emphasis on large-scale production at minimum cost.[6]

By some accounts Henry Ford's historic contribution to "mass production" was achieved primarily by enforcing rigid quality control in parts manufacturing--utilizing the scientific management methods of F.W. Taylor (Taylor, 1911)--thus finally eliminating the need for "fitting". He himself stressed the combined principles of "power, accuracy, economy, system, continuity and speed"[7]. Ford engineers certainly looked everywhere for opportunities not only to subdivide the manufacturing process into many individual tasks, and to

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[6] As a point of interest, the U.S. Bureau of Labor Statistics, Dictionary of Job Classifications does not include the category "fitter". However in many European countries the term "fitter/assembler" is standard.

[7] Quote from Ford's article "Mass Production" in 13th edition of Encyclopedia Britannica (1926), cited by Hounshell (1984).

increase the efficiency of tasks by application of Taylor's methods, but also to substitute machines wherever possible for human workers. "Bringing the work to the man" was one of the ways to increase efficiency. Conveyor belts and gravity feeders began to be introduced extensively in the Highland Park plans by 1913. The moving assembly line (c. 1916) was the logical outcome of this rationalization.

Ford's assembly-line methods did, in fact, sharply reduce the cost of assembly as compared to parts manufacturing in the second decade of this century. However, in a fundamental sense, the assembly line is nothing more than a scheme to permit a more effective division of labor. The technology of assembly itself has changed very little until the last decade or so, except to the extent that assembly-line workers have gradually acquired power-assisted tools (such as wrenches) and the like.

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, are long-since 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 minute productive labor time. By contrast, the same 600 machining operations carried out by skilled machinists in a job shop would have required 600 minutes of machinist labor and cost at least $2500 (Cook, 1975; Cross 1982). One of the ironies of this situation is that the specialized machinery typically used in mass production --for example, the large transfer lines and multi-spindle drilling and boring machines-- are themselves customized, one-of-a-kind investments.[a] If auto engine plants could be mass produced as auto engines are, the capital costs would drop by as much as 100-fold.

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 between batch and mass production. The value added of the US manufacturing sector in 1977 was about equally divided between these two categories, as shown in Figure 4. Batch manufacturing can be further divided into one-of-a-kind (piece) or very small batches and medium to large batches, as indicated in Figure 5. Unit cost difference 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 2 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

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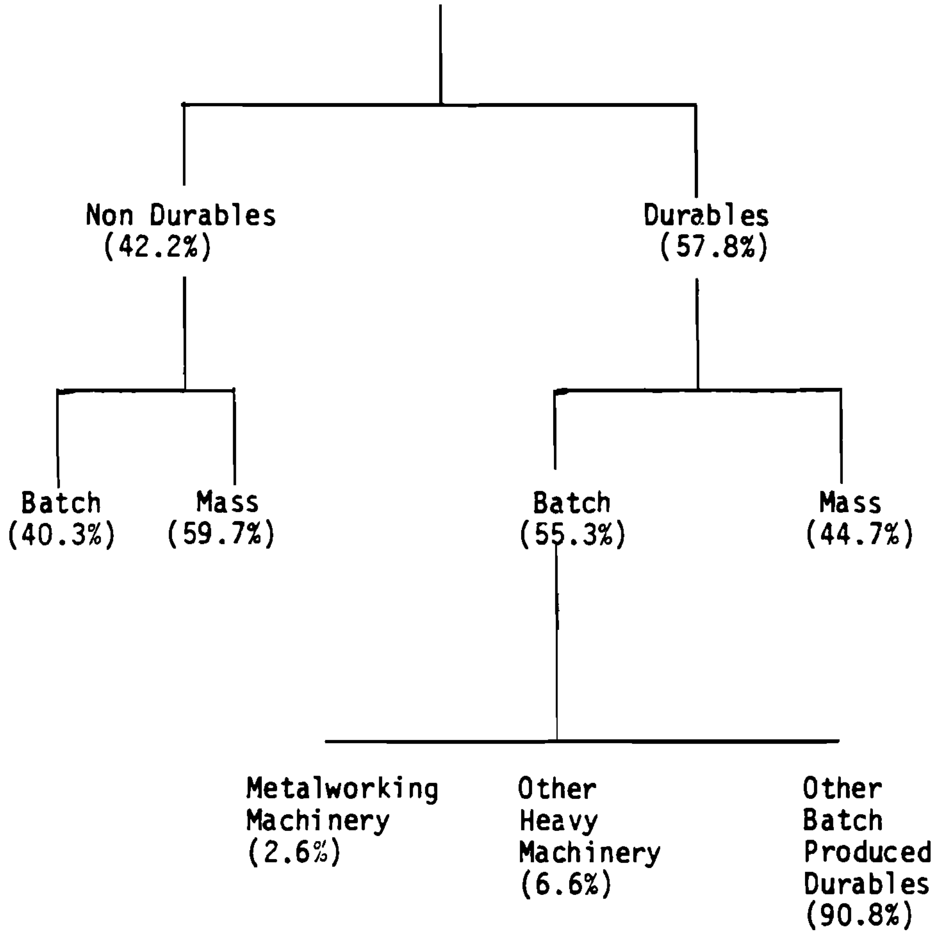
[a] The design of an auto engine plant, capable of producing 120 units per hour for 20 years, requires about 60,000 engineering man-hours (Cross, 1982).

Figure 4

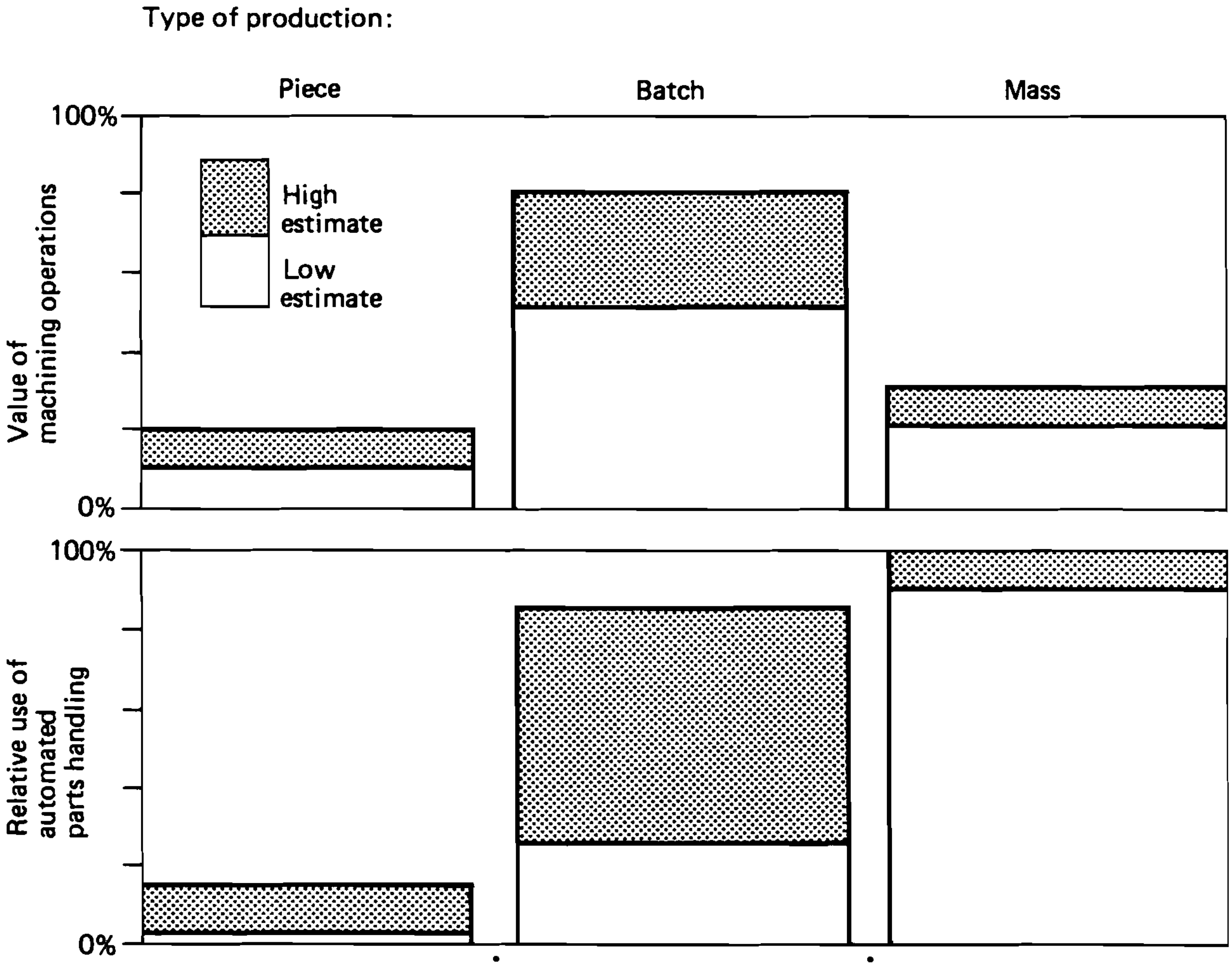
DISTRIBUTION OF MANUFACTURING VALUE ADDED
TOTAL V.A = $585,165 MILLION (1977$)
100.0%



Source: S. Miller, 1983
(PhD Thesis)

Figure 5

CHARACTERISTICS OF METAL PRODUCT MANUFACTURING



Typical lot size	Large complex part	1-10	10-300	Over 200
	Small simple part	1-300	300-15,000	Over 10,000
Typical products		Aircraft, large turbines. centrifuges	Marine engines, large electric motors, tractors	Autos, fasteners, small appliances
Typical machines		Manual, stand-alone NC	NC with auto part-handling, machining cell, flex mfg. syst.	Transfer, dedicated special machine

Source: American Machinist, 1980
(Special Report 726, Oct, 1980)

Table 2

Comparison of Manual Manufacturing Steps Elimination by Various Degrees of Automation

		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

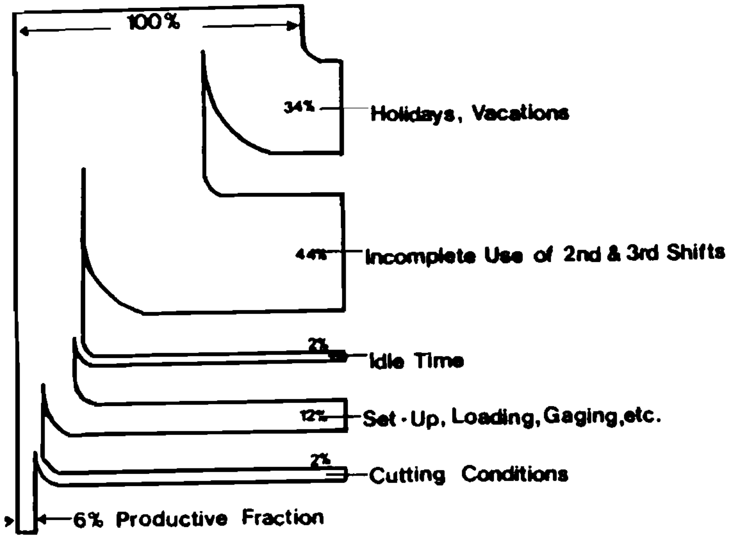
Source: General Accounting Office (1976: 38).

function of scale of production are shown in Figures 6(a, b, c). It is noteworthy that in a typical job shop machines are only tended about 20% of the time and only 6% is used for productive cutting. This contrasts to 22% productive cutting in a mass production facility (American Machinist, 1980)

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 1,000 tools, mainly drills, cutting simultaneously. The spindles are clustered in groups (or stations).

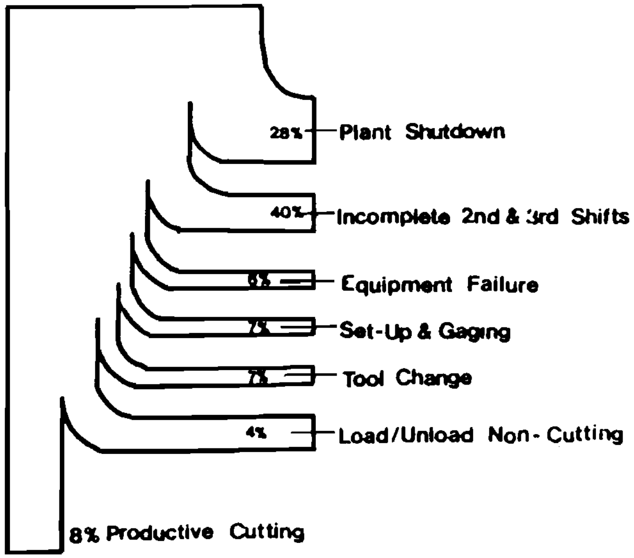
The mechanical requirements are exacting. Each of the spindles in each station must be permanently positioned very precisely with respect to all the others. All the spindles in each group must also be exactly synchronized, so that the resulting holes are not only parallel but also drilled to the exact 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



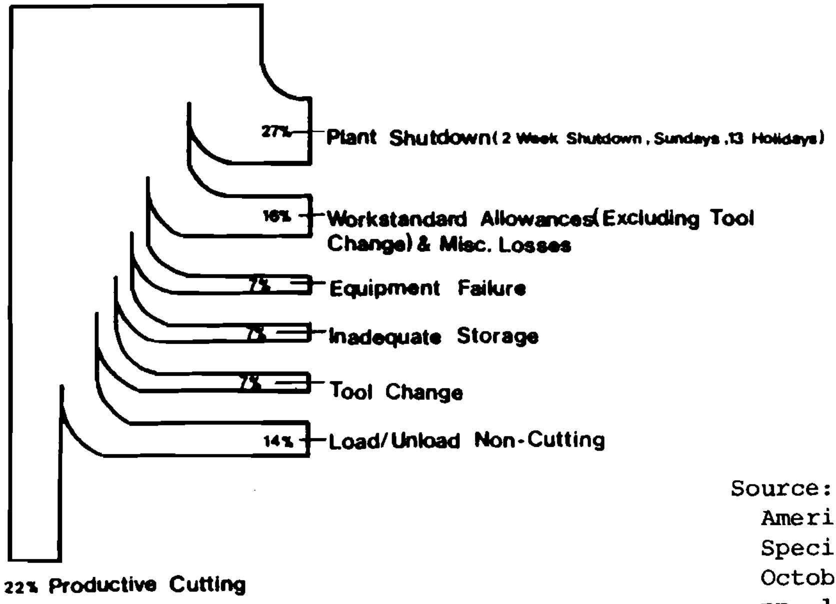
LOW-VOLUME MANUFACTURING

FIGURE 6A



MID-VOLUME MANUFACTURING

FIGURE 6B



Source:
American Machinist
Special Report 726
October, 1980
pp. 112-113

HIGH-VOLUME MANUFACTURING

FIGURE 6C

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 1970's were not able to convert plants making eight-cylinder engines to six-cylinder engines. For the same reason, a plant dedicated to making conventional transmissions and drive shafts for large rear-wheel-drive vehicles be converted to manufacturing transaxles for front-wheel-drive cars.

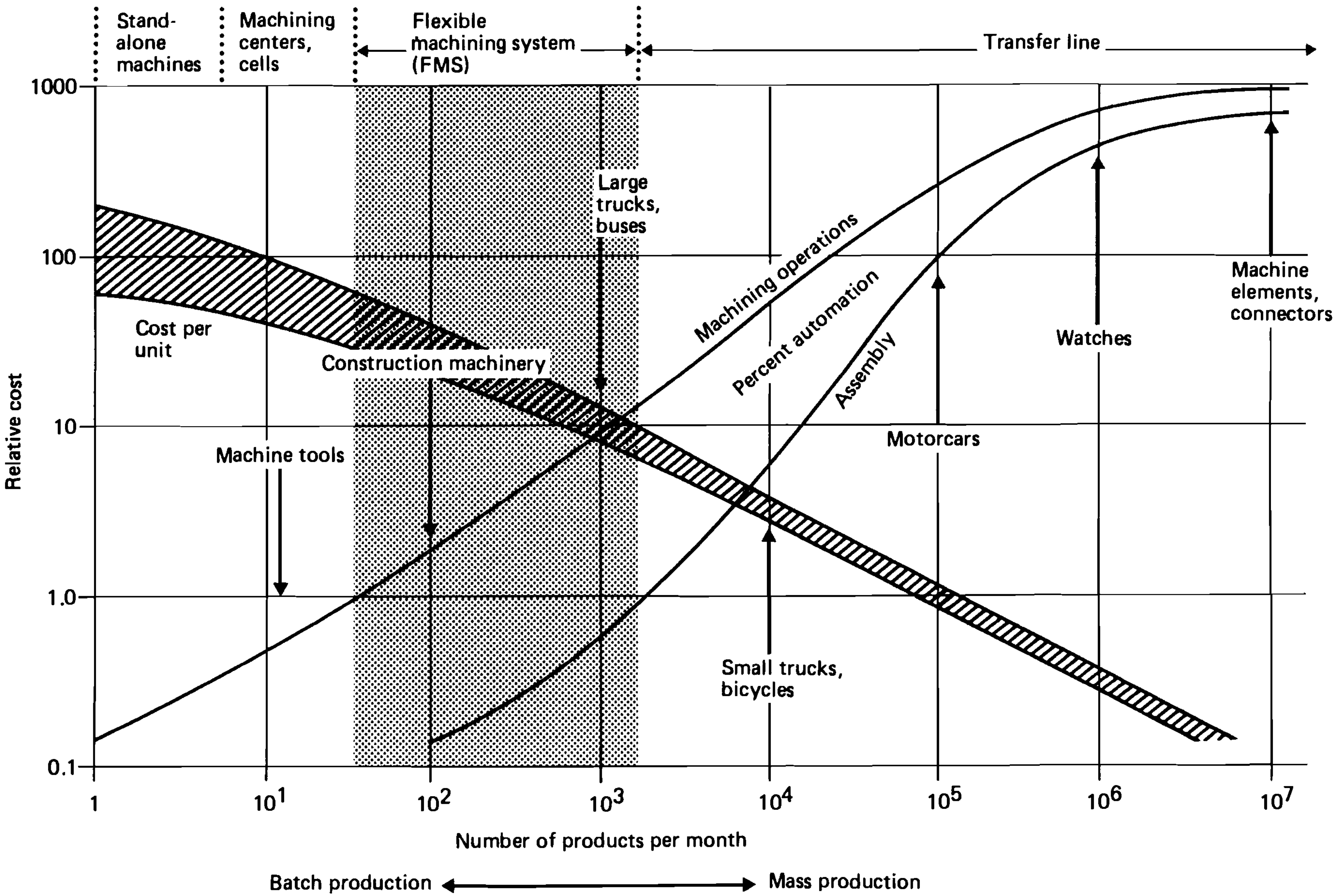
The economics of such special purpose automation, as compared with other modes of manufacturing is indicated schematically in Figure 7. The curve represents the cost-minimizing choice as a function of scale of production. Evidently, fixed costs are very high but variable costs (mostly labor) can be minimized. Thus hard automation pays off when production volumes become large enough.

<u>The Trend Toward Product Complexity</u> (Ayres, 1986)

The introduction of mechanization, interchangeability and standardization of parts, flexible machine power control (electrification), high speed steels and faster cutting tools, and mechanical transfer systems did not occur in a vacuum. The imperative demand for ever higher performance has forced products themselves to become increasingly complex and precise. A Colt revolver or a musket (c. 1850) would have required fewer than 20 parts, all of which could be made in the same armory. An all metal (brass) Jerome clock of the 1830's would have required fewer than 100 parts, of which about 10 were moderately complex gear-wheels and escapements (stamped) and the rest were mostly bolts, nuts, pins, axles, bushings,

Figure 7

COSTS AND AUTOMATION vs. VOLUME



Source: Author, adapted from various sources washers, and flat stamped casing parts. Almost all of these parts were probably made in the same plant. An early sewing machine (c. 1860) would also have required around 100-150 parts, including some stamped parts, several castings, a number of standard items like bolts, nuts, washers, axles, pins, several gear wheels and a few complex parts requiring machining or forging (Hounshell, 1984). A minor proportion of these parts were probably purchased.

Ball bearings began to replace sleeve bushings in the 1870's and represented a sharp increase in mechanical complexity. They found an important application for the first time in bicycles (c. 1885). This period probably also marks the beginning of the trend toward subcontracting for specialized mechanical components. A bicycle uses 5-6 ball bearings each consisting of 12-20 steel balls rolling between 2 steel races. The bicycle chain consists of around 300 individual parts, and the lightweight spoke wheel involves a rather complex hub, an outer rim, and 30-40 spokes with threaded ends plus several fasteners. Altogether, a multi-speed bicycle requires around 800 distinct parts. The typical bicycle manufacturer of today is likely to produce only the welded frame and some key parts like the wheel hubs and derailleurs. Most other parts are purchased from subcontractors, including the ball bearings, nuts and bolts, cables, chains, bushings, gear wheels, tires and other plastic, glass or rubber items.

Early automobiles were largely based on bicycle technology, with the addition of a crude internal combustion engine. A rough estimate for an early motor-car (c. 1900) would be 1500-2000 parts, mostly simple adaptations from bicycles or carriages. Later models have become far more complex in almost every way, except for the substitution of stamped metal wheels for bicycle-type spoked wheels. Nevertheless, automobiles at the present time require more than 20,000 distinct parts of which only 10-15% are produced by the name-plate manufacturer. A modern industrial circuit-breaker requires 1300 parts, while a 1970's IBM Selectric typewriter requires 2700 distinct parts. Roughly speaking, consumer products increased in complexity by a factor of 10-15 from 1830 to 1900 and by a similar factor of 10-15 from 1900 to 1980.

When the large number of different models of complex modern products are considered, the problem of organizing production (and subsequent service) becomes truly staggering. A major manufacturer of electrical connectors (AMP) produces 80,000 different types. IBM's Selectric typewriter was made in 55,000 different models. Westinghouse Electric Co. (c. 1983) manufactured over 50,000 different turbine wheel shapes for its steam turbines. Caterpillar Tractor Co. (c. 1985) had over 25,000 different subcontractors making various component parts of its machinery products. The so-called major manufacturers have to a large extent become "systems integrators", providing only some of the more specialized parts and final assembly of subsystems from a network of suppliers. Their major economic role is design, marketing, and service, not production per se. For such firms, direct manufacturing labor constitutes a minor proportion of all costs, ranging from 15% to 25% or even less.

In summary, while the mechanization of parts manufacturing has not yet reached any physical limits, its contributions to gains in manufacturing productivity were becoming negligible by the 1970's. Even within the manufacturing arm of a big "systems integrator" logistics,[9] assembly, and quality control[10] now account for, by far, most of the real costs of manufacturing--quite apart from indirect costs of finance, marketing, personnel management and the like. To reduce costs significantly--and remain competitive--a completely new technology of production seems to be needed. This imperative will become increasingly manifest over the next several decades.

The alternative, of course, is to design the human worker out of the production system. Thanks to solid-state monolithic integrated circuits and large-scale integration (LSI, VLSI) modern computers are of the order of 100,000 times <u>less</u> error prone than human workers (McKenney & McFarlan, 1982). 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

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[9] The cost of "logistics" including materials handling, storage, inventory control and shipping, accounts for over 27% of manufacturing value added in Sweden (Agren & Wandel, 1983). A British study concluded that 19.5% of industrial labor costs are attributable to materials handling alone (Ibid). For the U.S. logistics accounts for 22.5% of manufacturing value-added (A.T. Kearney, 1984).

[10] Including inspection, monitoring, rework, etc. One survey showed that quality control averaged 5.8% of Sales or roughly 11-12% of Value added (Quality, 1977).

Programmable Controllers (PC's), which are another key ingredient of advanced forms of automation.

The first great breakthrough that made all of these modern developments possible was, of course, the development of semiconductor switching elements (transistors) by Bardeen, Brattain and Shockley of Bell Telephone Laboratories in 1948.[11] The microminiaturization trend has proceeded very rapidly, because of a "virtuous circle" of linked relationships. Each reduction in the physical size of a circuit element results in a corresponding reduction in the power required, per unit operation. This, in turn, reduces the requirements for heat dissipation and--in turn--permits higher operating speeds and more compact circuitry.

The performance of a computer, telephone switchboard, TV set or radar navigation system tends to be closely related to the number of distinct circuit elements it embodies. On the other hand, the more elements there are the more interconnections there must be. It was recognized very quickly in the 1950's that manual processor especially that of interconnection (i.e. assembly) would soon be the limiting factor in electronics.[12]

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[11] Actually, the first generation of programmable electronic computers beginning with ENAC (designed and built by Eckert and Mauchly at the University of Pennsylvania in 1947) used vacuum tubes. The first transistorized computer was that IBM 704, introduced in 1956-57.

[12] In this context, J.A. Morton, Vice President of Bell Laboratories, coined the phrase "tyranny of numbers" in 1958. He pointed out that scientists know in principle ways of constructing (digital) electronic devices to extend human visual, tactile and computational abilities, but that such systems can require "hundreds, thousands, tens of thousands of electron devices", each of which "must be made, tested, packed, shipped, unpacked, retested and interconnected on at-a-time" (Reid, 1985).

Luckily, the number's barrier was broken almost as soon as it was recognized. The second big breakthrough in 1959-60 was the so-called integrated circuit (lc), which combined transistors with other components (capacitors, inductors, resistors, etc.) composed of a multi-layer "stack: of thin films deposited on an insulating ceramic substrate. This discovery is jointly attributed to Kilby at Texas Instrument Corporation and Noyce at Fairchild.

The integrated circuits (IC's of the early 1960's have been followed by several generations characterized by ever smaller individual circuit elements packed more and more closely on a single "chip". The first generation (1960-1965) is sometimes small-scale integration (SSI), referring to devices with up to 10 "gates" or bits of memory per device. The second generation (1965-1970) was medium-scale integration (MSI), characterized by 10-100 gates or bits of memory per device. The third generation known as scale integration (LSI), arrived about 1970 with Intel's introduction of the 4-bit microprocessor in 1971 and the first (1K) random access memory (RAM) on a single chip in 1970. Very large Scale Integration (VLSI) corresponds roughly with the microcomputer-on-a-chip and the 16K RAM (c. 1977), while ultra-large-scale integration (ULSI) corresponds roughly with Western Electric's first million bit RAM (c. 1985). Progress has accelerated, is anything: in early 1987 NTT (Nippon Telephone & Telegraph) announced a generation-skipping 16 million bit RAM chip.

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 human must be rigorously kept away from the actual manufacturing steps because of the danger of contamination. The major elements of cost are now the design and the specialized capital equipment.

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 less than 4 years ago (1983), is now selling at $4 or $.00156 per bit. Price trends for logical functions are shown in Figure 8 and for random access memory in Figure 9. In relative terms, costs have declined by a factor of about 1-million since the era of vacuum tubes. Impacts on system costs are summarized in Table 3.

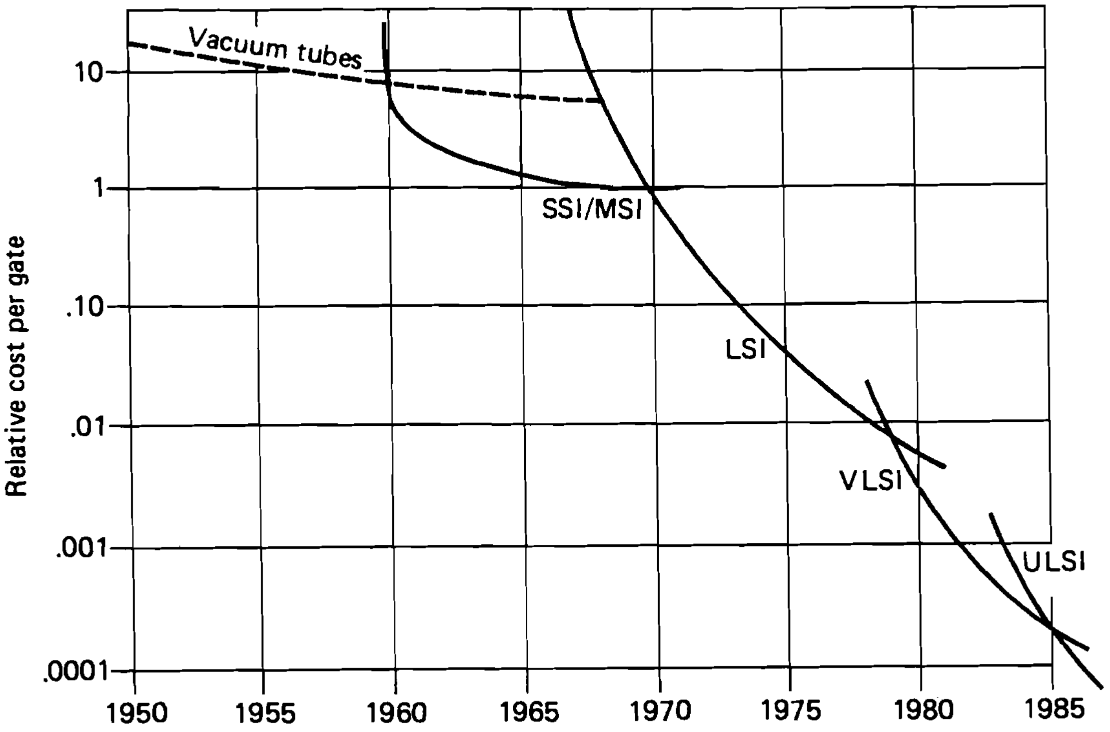
It scarcely needs to be said that further technological improvements and corresponding cost reductions seem virtually assured by the enormous R&D resources currently being invested in these areas. A number of major new technologies, including optical devices and organic chemical molecular (molecutronics)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

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 1948-53 period under the sponsorship of the US

Figure 8

COST REDUCTION FOR LOGICAL FUNCTIONS



Source: Author, from various sources

Table 3

COST IMPACTS OF MAJOR
MICROELECTRONIC DEVELOPMENTS

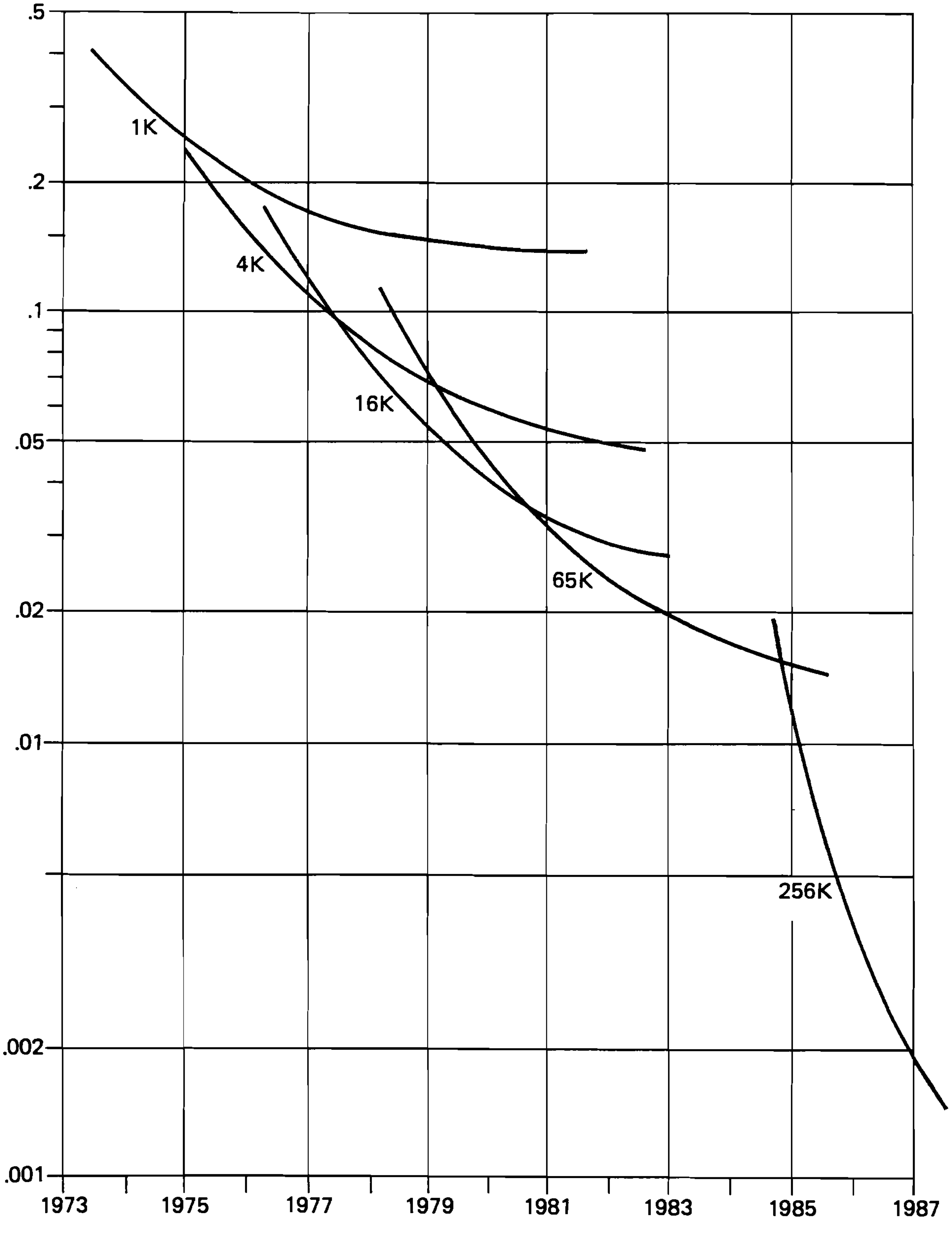
Evolutionary step	Components to assemble	Component and assembly costs*	Cost ratio
1. Discrete-component systems (transistors, resistors, capacitors, etc.) DISCRETE	20,000 – 30,000	$6,000 – $9,000	—
2. Integrated circuits (small-scale integration—less than 10 gates or bits of memory per device) SSI	350 – 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.

Source: NIRA, 1985

Figure 9

COST REDUCTION FOR RANDOM ACCESS MEMORY



Source: Author, from various sources

AirForce. NC controls were offered commercially in 1954. 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 multi-axis 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, e.g. for the aerospace industry.

Adoption of the first generation NC machines was slow. By 1963 only about 2000 NC machines were in service in the U.S. One reason was the high cost of controllers. An early (1958) transistorized control unit cost $70,000-80,000. By 1968 this had fallen to $30,000. An improved controller employing integrated circuity (c. 1974) cost $15,000 (Quantum Science, 1974). Application of LSI[19] technology in the early 1970's brought the costs down even faster while simultaneously providing for vastly increased capability. A minicomputer costing $ 30,000 in 1974 is vastly outperformed today by a micro-computer costing $1500. Moreover, the increased availability of computer power in the early 1970's also permitted the introduction of far more flexible machine controls, known as computer numerical control or CNC. The first generation of <u>adaptive</u> controls, featuring force feedback

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[19] LSI = Large-Scale Integration

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, or DNO). 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 1990's and beyond, software will be the only cost factor affecting the choice between manual and CNC machine tools or other programmable devices.

The early 1970's was a period of rapid improvement in the basic technology of machine control due primarily to the introduction of microprocessors in 1969 by Intel Corporation. Microprocessors and pressure/torque sensor were successfully adapted to machine tools (and robots) in 1973-74. Moreover, modular program packages were becoming available which cut programming time for CNC systems by a factor of 3 from 1971 to 1974 alone (Ibid). Perhaps partly as a result, the average cost of CNC machine tools purchased actually stopped declining in the early 1970's (Figure 10). 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 trend toward "user-friendliness" has continued. So-called 4th generation languages of the 1980's exemplified by FOCUS, MARK V, RAMIS, IDEAL are far more user-friendly than COBOL or FORTRAN, the assembly languages of the 1960's. 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 (Quantum Science, 1974). The reality was a much more modest (though still noteworthy) growth in the use of NC/CNC. Still, by 1983 NC and CNC machines accounted for 1/3 of all new machine-tool purchases in the U.S. (Figure 11), 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 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.

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. Again, initial acceptance was very slow. By 1970 only about 200 robots were in service in the U.S. The first Japanese robot appeared in 1969 (Kawasaki, a licensee of Unimation). Demand picked up somewhat in the early 1970's. By 1974, when CNC capabilities became available there were about 1100 robots in service, and expectations exploded. (An optimistic 1975 market report anticipated that 24,000 robots would be in service by 1977[14]). The real number

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[14] Weinstein cited by Eikonix, p. 165.

Figure 10

THE UNIT PRICE OF NC-MACHINE, USA

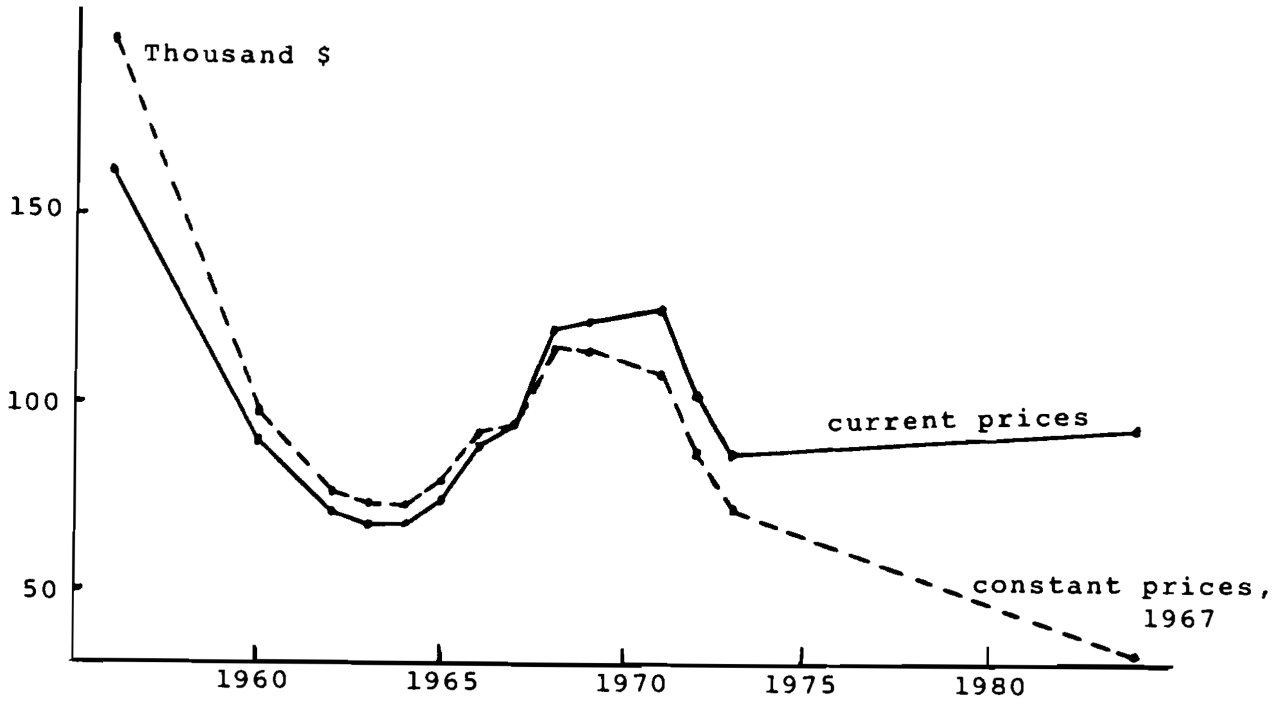
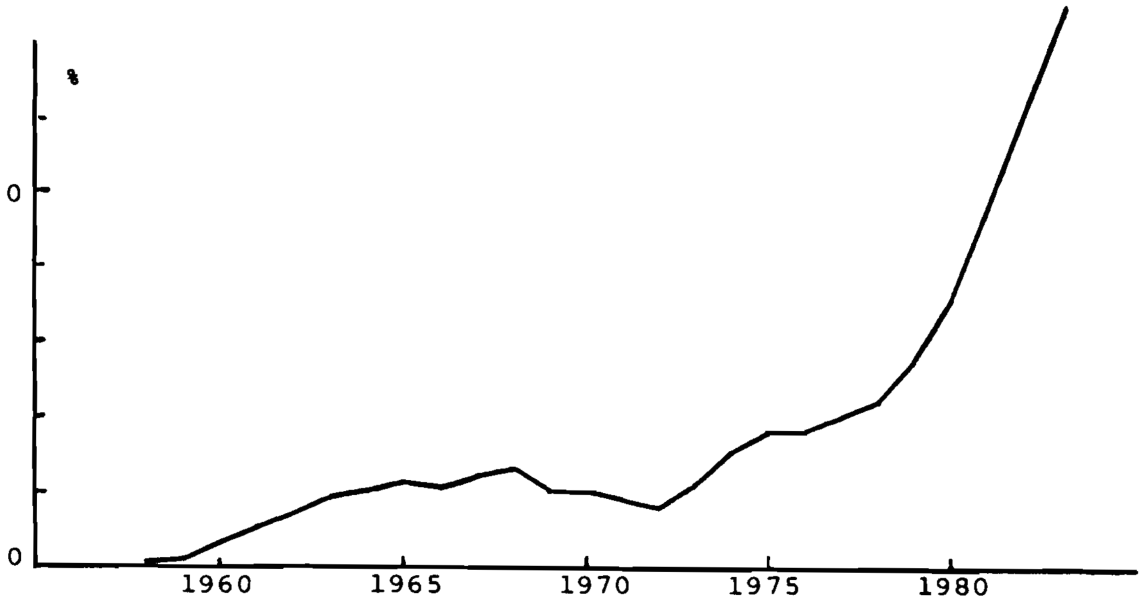


Figure 11

THE SHARE OF NC-MACHINES IN TOTAL
METAL-CUTTING MACHINES PRODUCED, U.S.



Source: I. Tchijov (IIASA), 1986

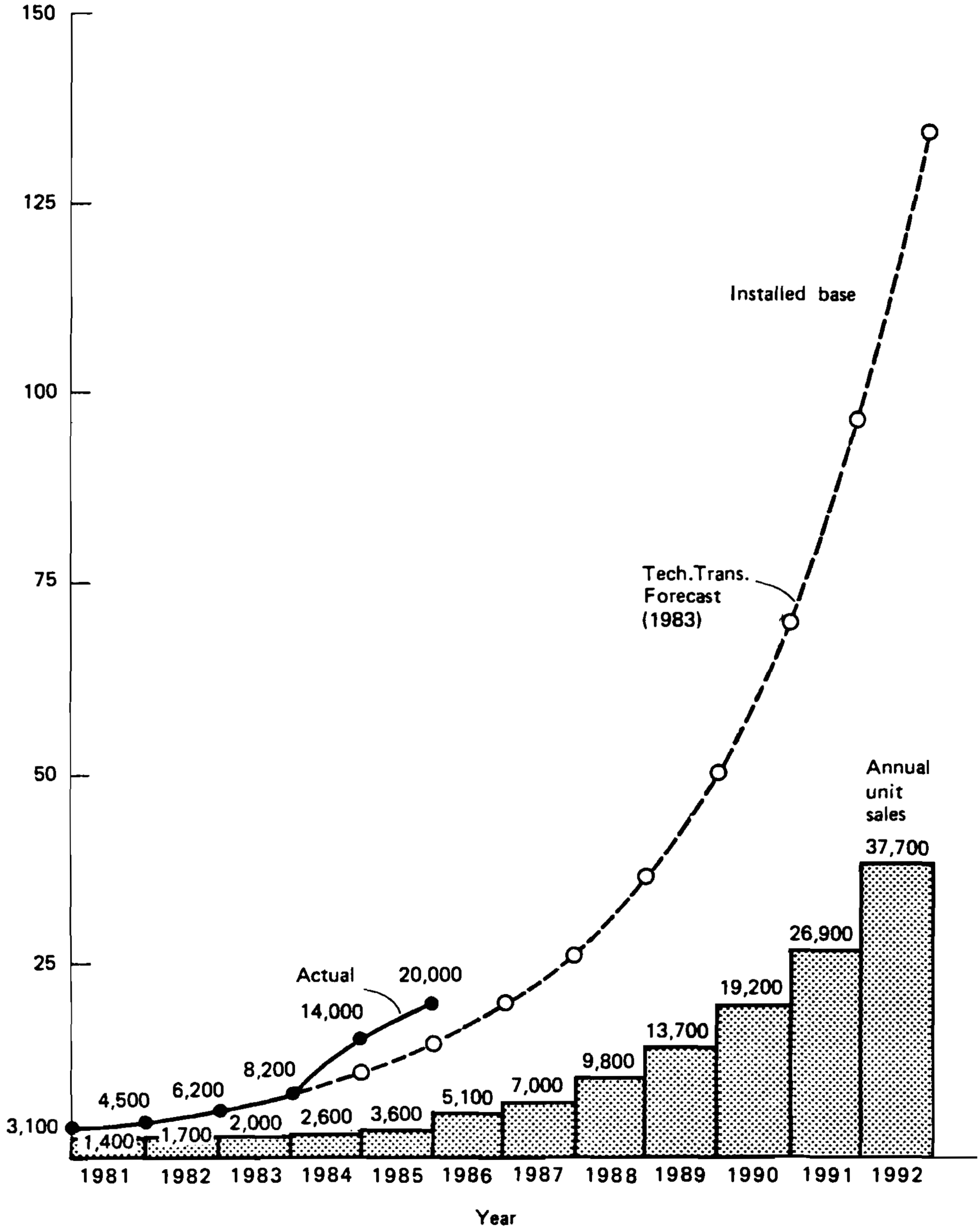
was less than 10% of that. The 24,000 level was probably achieved sometime in 1986 (Figure 12).

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 1980's are substantially more accurate and better coordinated (e.g. 2-hand control) than robots of the 1960's.

Programming languages for robots are diverse and still relatively clumsy. Thus engineering costs for new applications tend to be quite high--up to 2x the cost of the robot itself--which is a major impediment to small and first-time users (Miller, 1983). 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). Several recent forecasts by different groups put the total number of robots in service in the U.S. by 1990 in the range of 50,000 to 150,000 and annual sales in the multi-billion dollar range. For example, a 1983, study Tech. Trans Corp., cited by OTA (1984), estimated that about 50,000 robots would be in service by Jan. 1, 1990. (However, actual

Figure 12

ACTUAL AND PROJECTED U.S. ANNUAL ROBOT SALES AND INSTALLED BASE THROUGH 1992



NOTE: The projections above are highly speculative. Robot sales have not grown nearly as fast as most industry observers expected, and one industry analyst suggests that the above figures may be as much as 30 to 50 percent too high. (E. Lustgarten, Vice President, Paine, Webber, Mitchell, Hutchins, Inc., personal communication, Feb. 7, 1984). On the other hand, robot vendors and the Robotic Industries Association still believe that a tremendous upsurge in robot sales is forthcoming, and the projections above may even be too low. (L. Lachowicz, Robotic Industries Association, personal communication, Feb. 7, 1984). See ch. 7 for further discussion of the robot industry and its prospects.

SOURCE. Tech Tran Corp., *Industrial Robots: A Summary and Forecast*, 1983.

Adapted from OTA (84)

robot sales in 1984 and 1985 were sharply higher than Tech. Trans expectations).

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 1980's is the addition of vision and/or tactile sensors and feedback control to robots. Adaptive control units for machine tools, based on pressure/force sensors, were first marketed as early as 1972-73. Actually, the earliest robots with "vision" were built in the mid-1970's, (Bendix) but they were not introduced to the market and the project was abandoned.

Flexible (Batch) Manufacturing: FMS and LS/FMS

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

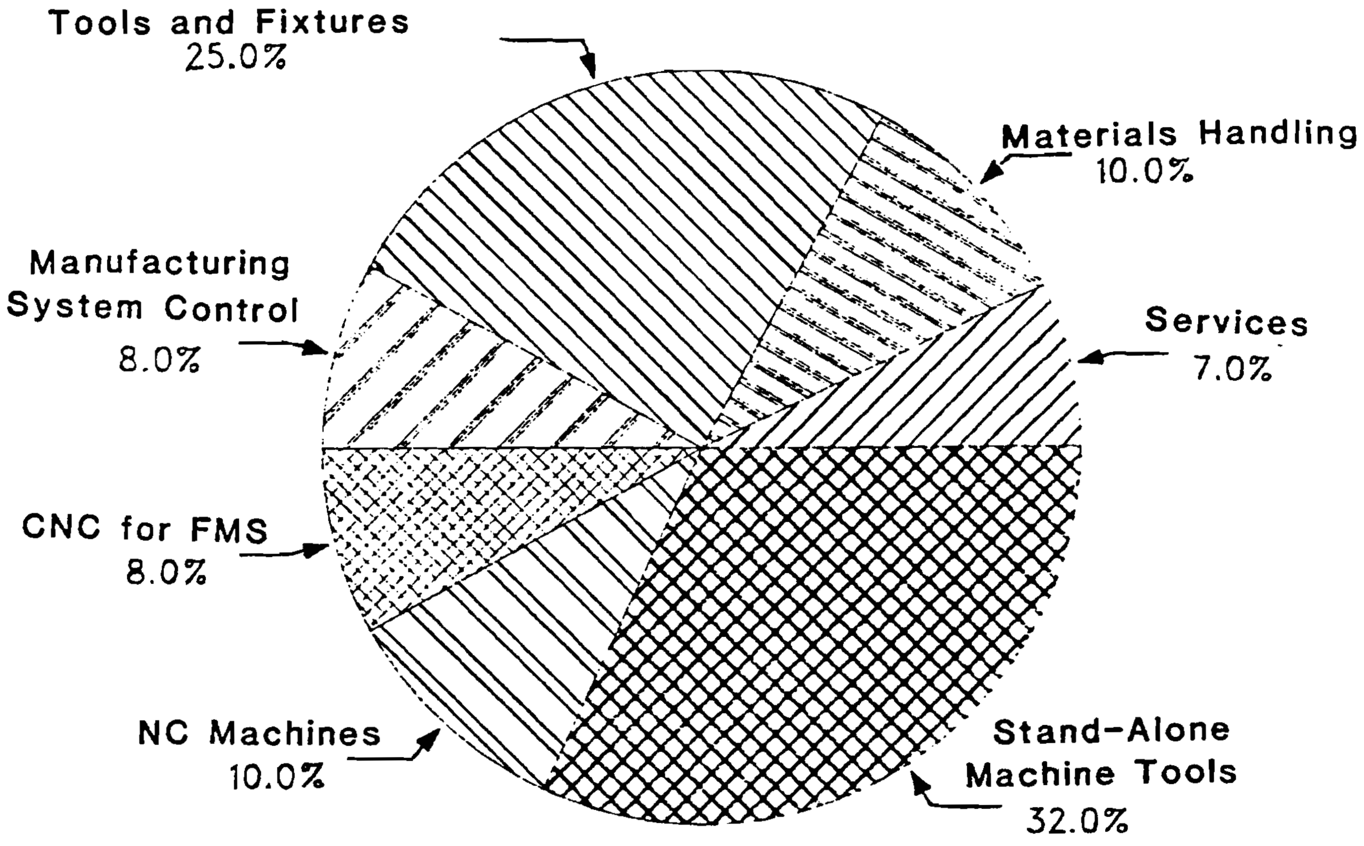
In a modern sophisticated flexible manufacturing system (FMS, palletized workpieces of different types randomly travel between and processed at various programmable, multipurpose machine tools and other work stations. Parts flow through the system according to individual processing and production requirements,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

The flexibility of an FMS is not achieved without cost. A transfer line and an FMS both need basic machine drives workheads, materials handling system, and tools. But the flexibility of an FMS requires variable speeds and cycles, numerical (i.e. digital) controls and a supervisory computer to coordinate cell operation (see Figure 13). 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. Expressing this cost breakdown as a relationship between cost and control capability, it is clear that the implemented cost increases as the level of control increases (Table 4). 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 percent, 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. Many of the 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 cost of the FMS.

Figure 13

MANUFACTURING SYSTEM (FMS) HARDWARE COSTS (1984)



Source: Data from Kearney & Trecker, Inc.

Table 4

Cost of Machine Tool Controls ($\$ \times 10^3$) In FMS

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

The net result of falling costs and increasing complexity of computers and NC machine tools is likely to bring down the hardware cost of flexible manufacturing systems, since these components are integral to the functioning of an FMS.

An obvious implication of the above discussion is that the hardware cost of flexible factory automation can be cut sharply (perhaps 3-fold or more) by deliberately utilizing more standardized equipment modules that could themselves be manufactured in much larger batches.[15] This modules will necessarily be quite generalized in capability, i.e. with variable speeds and cycles and an exogenous system of electronic controls.[16]

Here the essential difference between small batch manufacturing in a multi-product plant and large scale or mass production of a single product becomes apparent. In small

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[15] Rapid Japanese penetration of the U.S. CNC machine tool market since 1980 seems to be based on this strategy.

[16] Determination of the appropriate control settings is done off-line, with the assistance of simulation models.

batch production (job shops) there is 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 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-along 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 equipment.

The generic large scale FMS (LS/FMS) will therefore consist of a number of "cells" buffered by intermediate storage, but operating synchronously <u>on the average</u>. 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 slow down or stop which is signalled 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).[17] Again, sensory feedback data monitors cell performance in real time, and deviations from the norm can result in a programmed shut-down 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 (Figure 14). If one cell is down the supervisory computer may instruct neighboring cells to continue to function temporarily, taking workpieces from buffer storage of feeding them into buffer storage. In a very sophisticated LS/FMS there may also be several cells, in parallel, carrying out the same sequence

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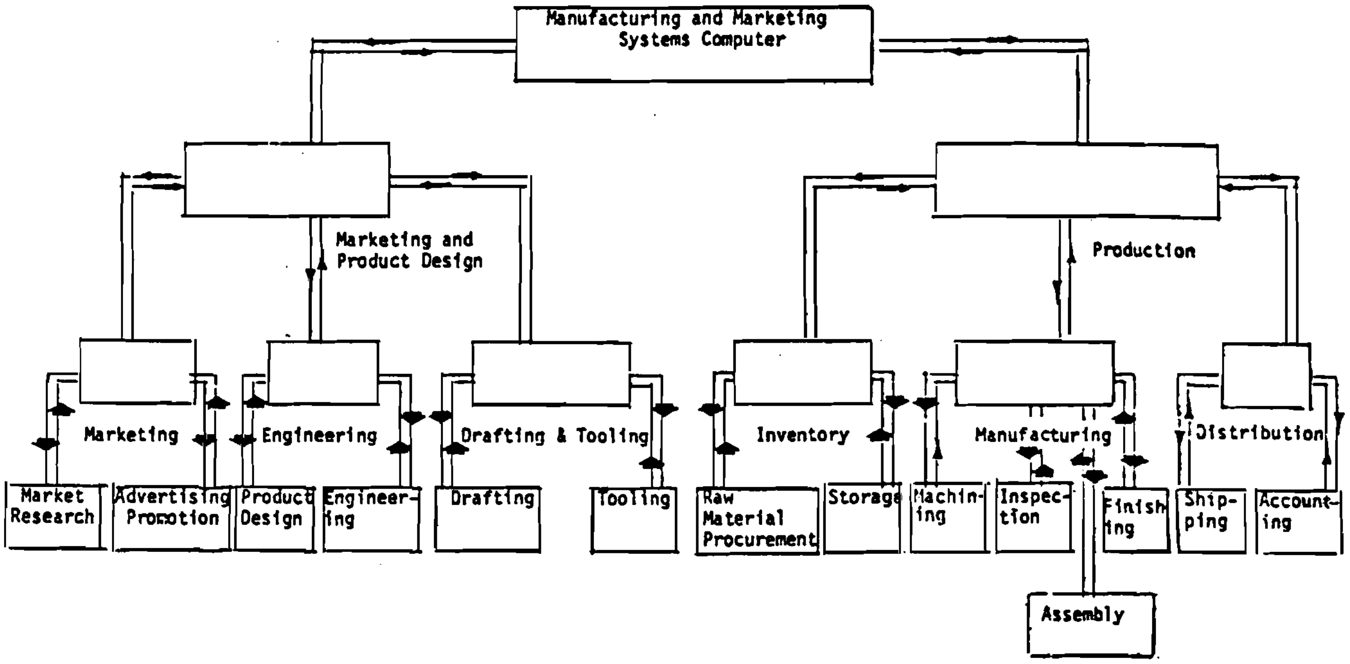
[17] Thanks to Paul Wright for this metaphor.

Figure 14



In a completely computer-aided design/computer-aided manufacturing operation there will be hierachies of computers. Thus, the information and control loop from any one point in the operation to any other point will be easily facilitated.

Source: Modern Machine Shop
1984, NC/CAM Guidebook

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 affect 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 multi-product "parts-on-demand" plant. In many respects, the control problems are similar to those encountered in a traffic flow network or continuous process plant, i.e. the buildup of non-linear 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 in the U.S. (compared to 4 at the beginning of 1975) and around 250 in the world (Sheinin & Tchijov, 1987). As shown in Figure 15 the rate of growth appears to be accelerating.[18] The technology now appears to be reasonably well established. A recent forecast by the Yankee Group (cited by ECE, 1986) puts the likely number of FMS' 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.

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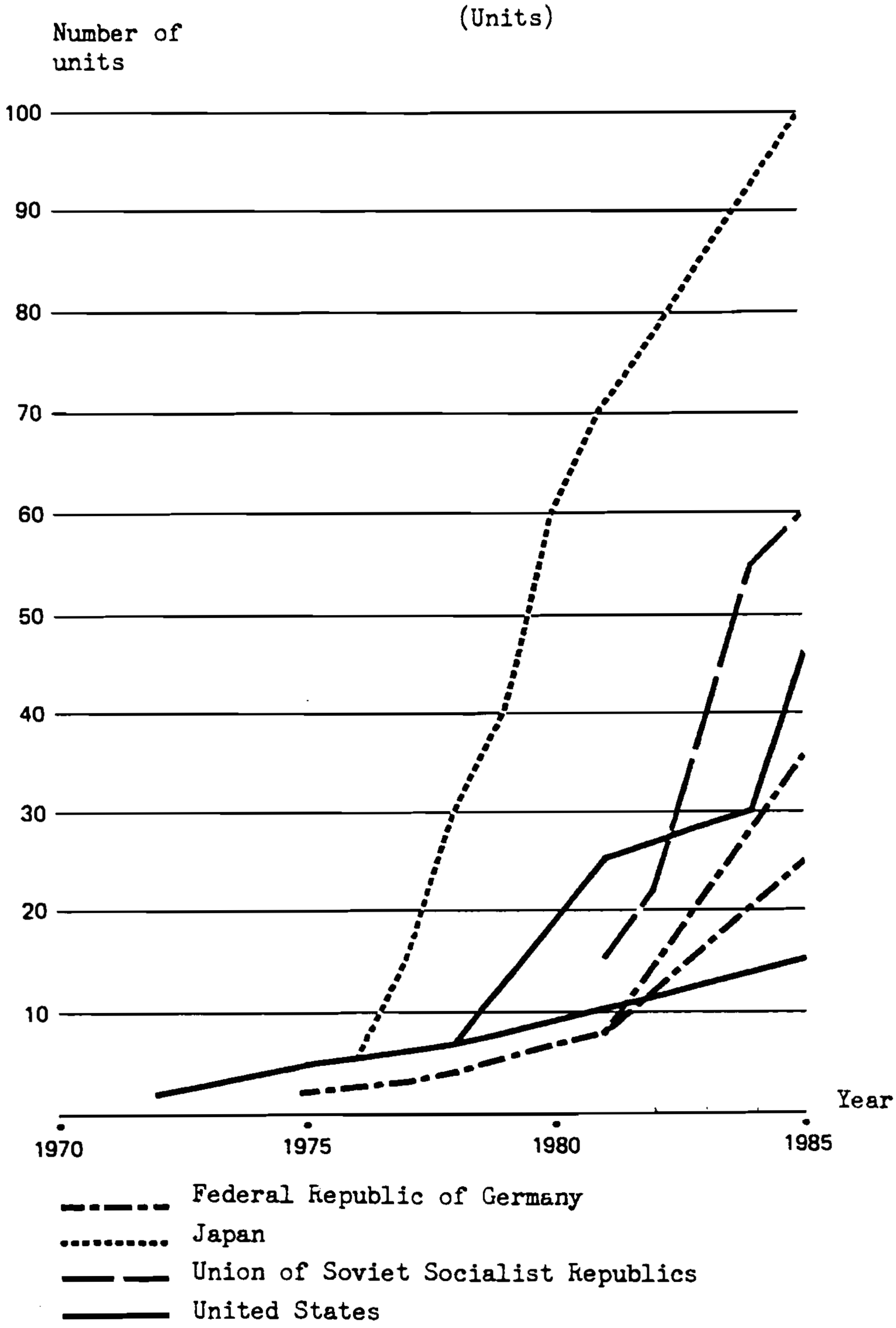
[18] As of 1985 the ECE counted 100 FMS in Japan, 60 in the USSR, and 36 in the Federal Republic of Germany (ECE, 1986).

FIGURE 15

Growth of FMS in the Federal Republic of Germany, Japan, the USSR and the United States

(Units)



Note: The two curves for the United States apply to a wider and a stricter definition, respectively, of FMS. For the Federal Republic of Germany, an interval estimate is given for the number of FMS installed at the end of 1984.

Source: ECE, 1986 (Figure III.1)

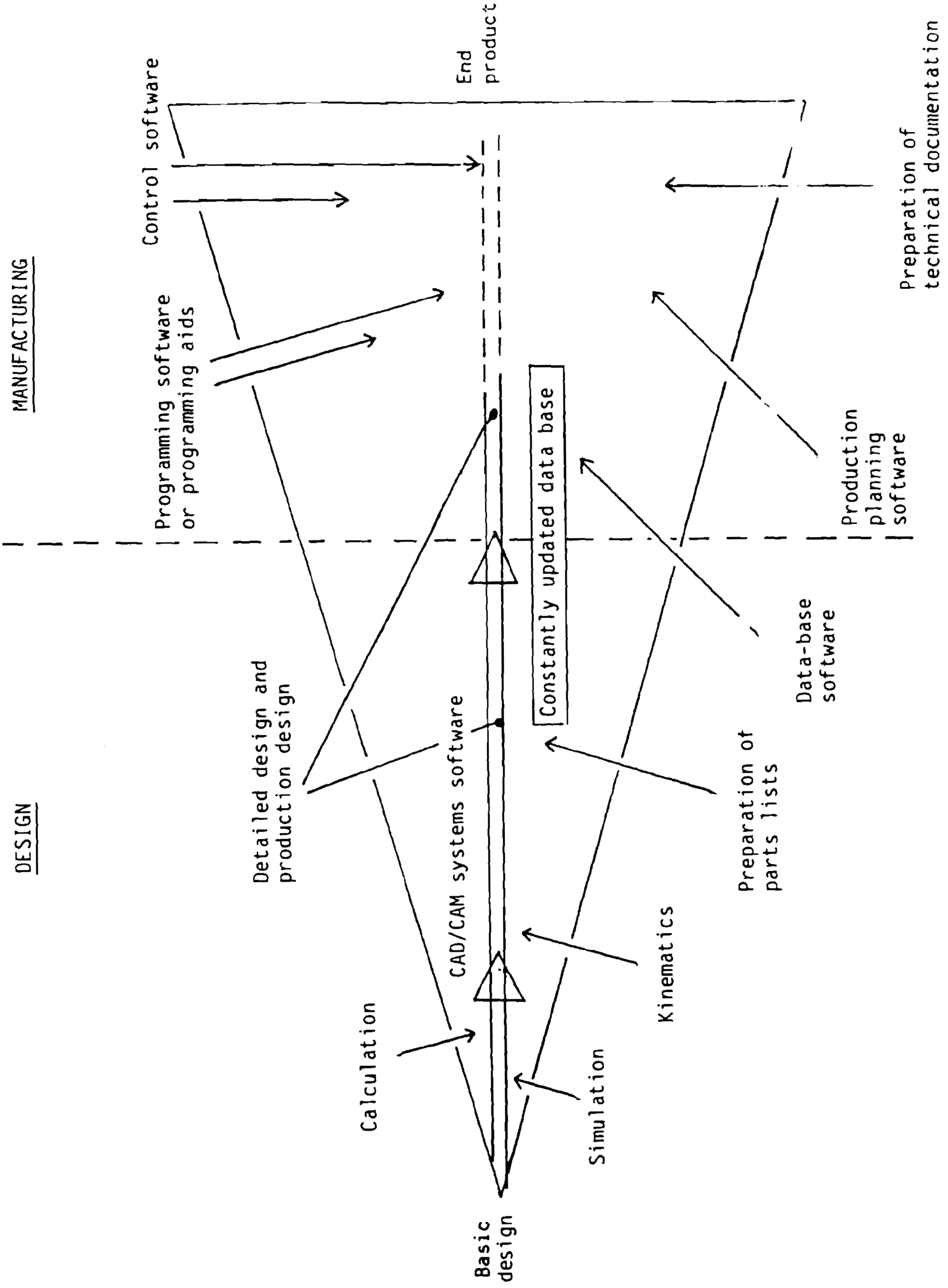
The first generation FMS systems are largely custom designed to produce a "family" of parts in small to medium batch sizes. Once built, they are not particularly adaptable to other sizes or shapes. However, as adaptive machine control technology becomes increasingly practical in the 1990's and machine 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 still subject to frequent design change.

CAD/CAM

The above acronym stands for computer-aided-design/computer-aided-manufacturing. These phrases are very nearly self-explanatory, except perhaps that it is unclear where "numerical control" (NC, CNC or DNC) becomes 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 "blue print" stage will eventually be by-passed. 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. Figure 16 illustrates the various functions of CAD/CAM systems. Figure 17 illustrates the progressive complexity of CAD applications with increasing emphasis on expert systems.

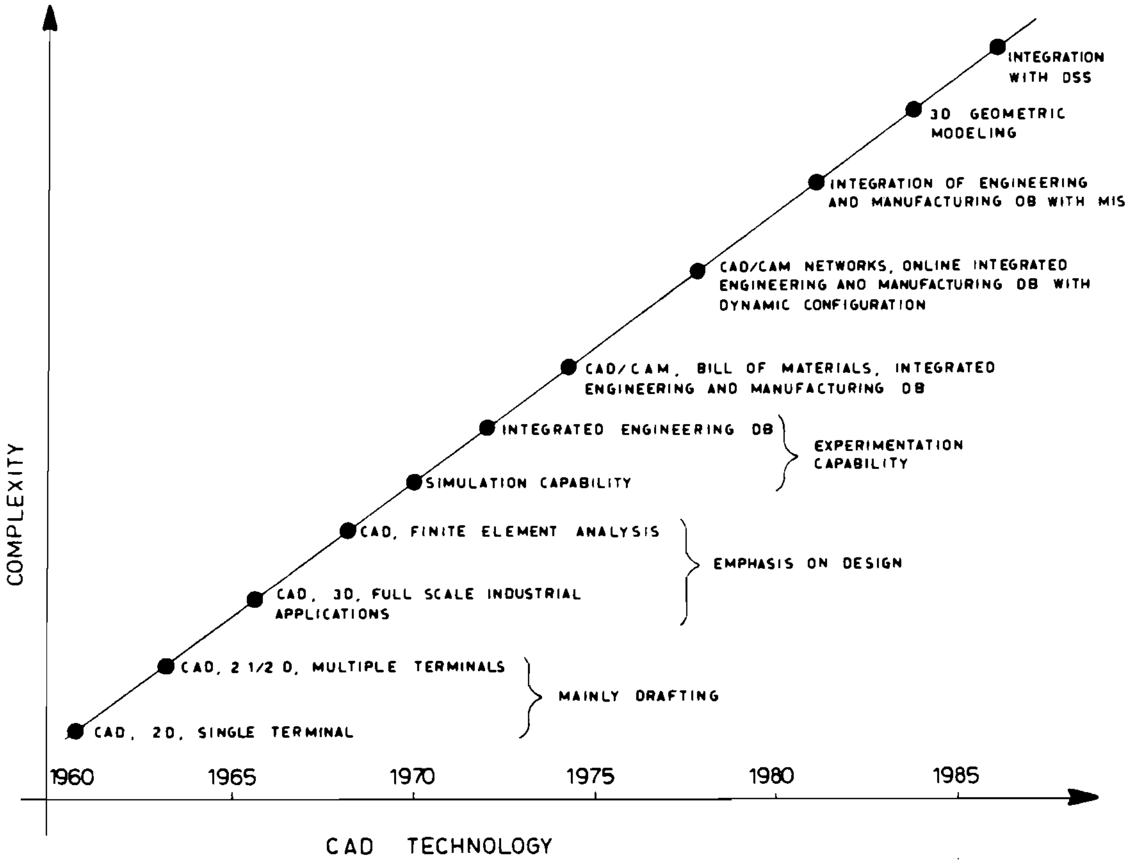
FIGURE 16

CAD/CAM software integration



Source: J.P. Durand, CFAO- Quels changements dans l'entreprise? CESIP, 1986 (case study- internal paper) Cited in Ebel & Ulrich (1987)

Figure 17



There has been an increasing amount of complexity, over 25 years of CAD implementation. In the future, complexity will be even greater and hence, the wisdom of using expert systems

Source: Chorafas, 1987

Computer Aided Design ((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 a small new firm (Computer Vision Corporation) introduced the first "turnkey" systems. 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 US firms). At least a $10 billion market is expected by 1995. (OTA 1984)

Unit prices are dropping as might be expected. 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 mini-computers. There were about 18,000 CAD installations in the U.S. in 1985, and probably 25,000 worldwide, with an average of 4 work stations per system.

It is expected that unit prices of systems sold in 1995 will be about 20% of current prices, with 70% of the performance. This is due to the increasing use of CAD adapted for 16-bit personal computers (PC's). It is estimated that 90% of CAD systems will be on 16-bit PC's by 1990 (Ebel & Ulrich, 1987).

There is much less information on the CAM market, since it is more diverse and most 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.

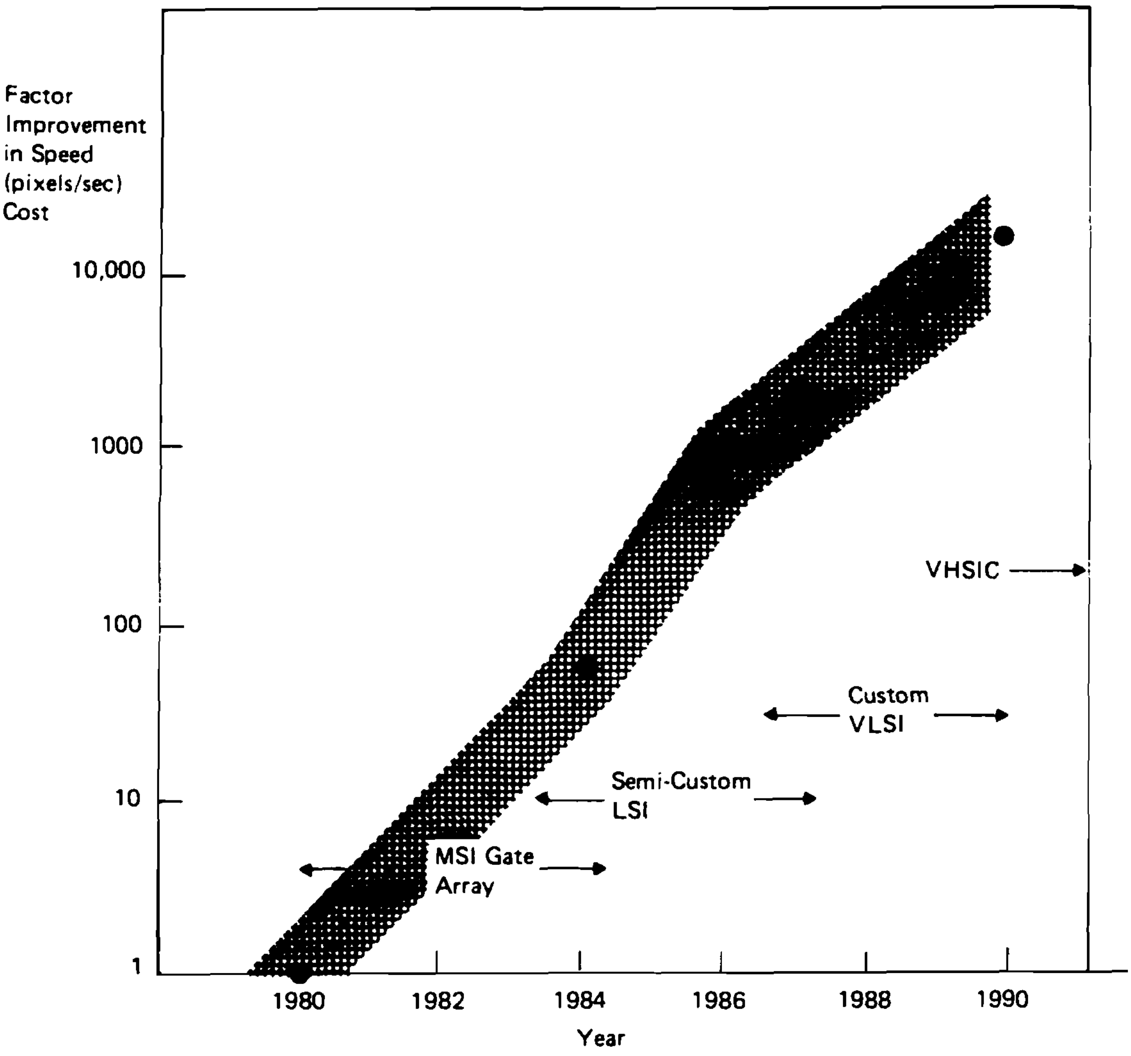
Machine Vision and Tactile Sensing

Machine vision systems became commercially available in the late 1970's 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 Figure 18. The first generation of vision systems required a fairly powerful minicomputer, which specialized software to process visual information (pixels/sec) and discriminate patterns of shapes by "neighborhood". These early systems were both crude and very slow. Vision technology of the mid-1970's was "binary". It detected and classified "blobs" based on their shapes, using statistical pattern recognition. A second generation of vision systems capable of discriminating "grey scales" and more sophisticated "syntactic" pattern recognition began to be available to commercial users in the early 1980's. 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

Figure 18

Estimated Improvements in Speed (pixels/sec)/Cost Ratio for Neighborhood Processing



Source: Funk, 1984

Table 5

FIVE GENERATIONS OF AUTOMATION

	Pre-Manual Control	First (1300) Fixed Mechanical Stored Program (Clockwork)	Second (1800) Variable Sequence Mechanical Program (Punched Card/Tape)	Third (1950) Variable Sequence Electro-Mechanical (Analog/Digital)		Fourth (1975) Variable Sequence Digital (CNC) (Computer Control)		Fifth (1990?) Adaptive Intelligent (AC) A.I. (Systemd 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 machinelevel stored program instructions modifed 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 Spectrum Analog (converted to digital) (e.g. voltm./ strain gauge)	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 microprocessor at machine level must pass visual& tactile info to higher levels to coordinate	High level controller has learning ability

Source: Author

"customized" VLSI chips. Such chips began to be produced in quantity by 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 (c. 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 judgement 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).

Employment Impact

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 1 robot for every 2 workers in the semi-skilled 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 hr/day operation is realized. On the other hand, robots will not replace all operatives--especially in smaller firms--for at least 3-4 decades. 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.

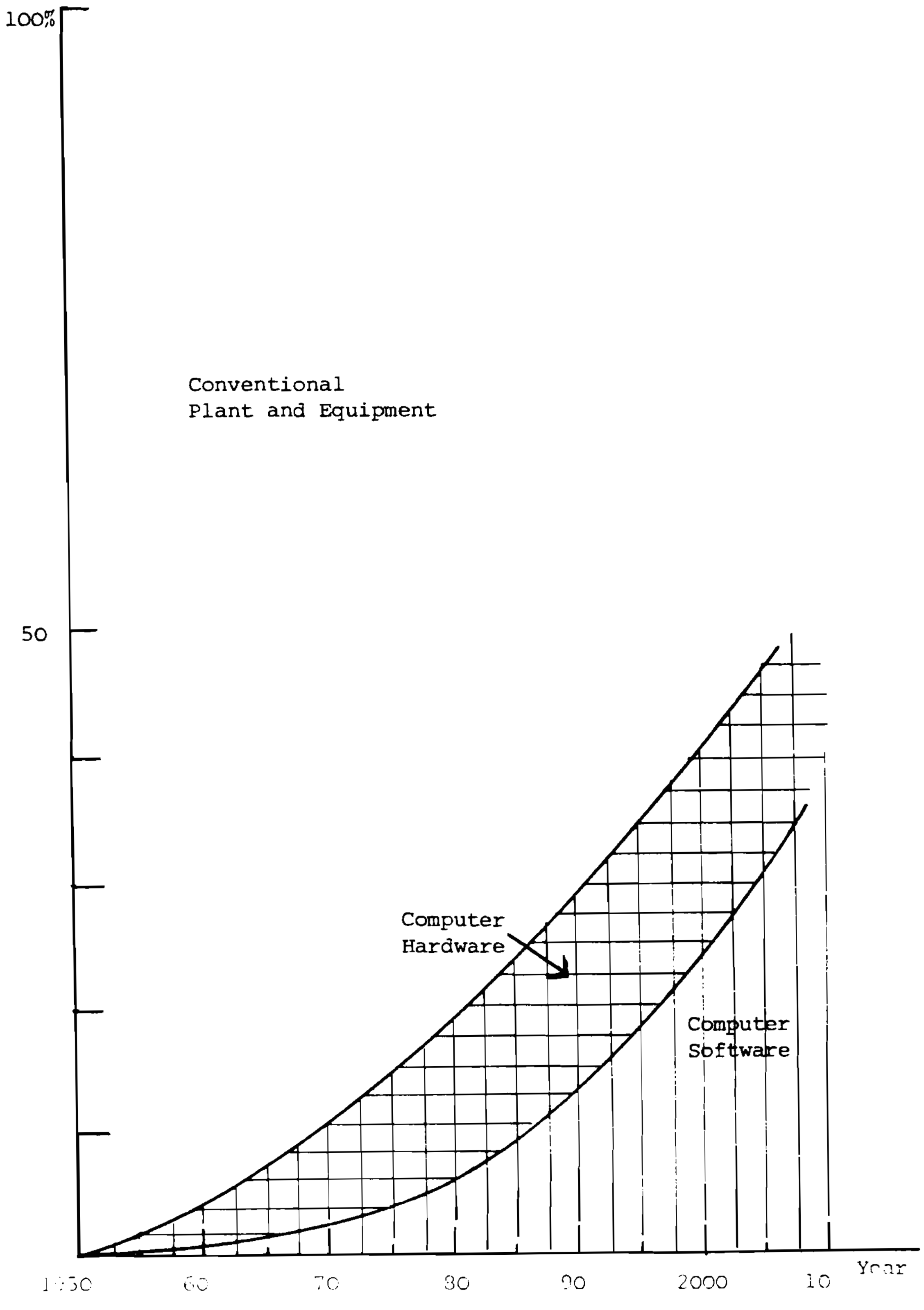
All things considered, the present level of penetration of robots, FMS, CAD/CAM and vision is probably not more than 1% of the maximum potential, and possibly less. This implies, among other things, that despite a considerable history, nothing much can be inferred about future rates of growth of the 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 over optimistic.

Several fairly strong conclusions can be drawn, nevertheless. On 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 seems equally robust is that the "software" component of capital will continue to grow in importance vis a vis the "hardware" component (Figure 19). The electronic hardware component (computers and electronic controls), which grew rapidly in the 1960's and 1970's, 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 60's. Issues of software in flexibility software compatibility and software productivity are now becoming dominant considerations in designing major systems. An increasingly

FIGURE 19

Composition of Capital Stock (Value)



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.

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 back 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.

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 1990's 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.

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APPENDIX A

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
G-M	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 - Georgia	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 - Georgia	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, Texas	Calculator assembly lines with robots.	?
United Technologies, Sikorsky Aircraft	Drilling and Riveting for aircraft assembly. <u>Includes</u>: 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. <u>Includes</u>: 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/hr). Uses photo diodes and color filters. 99.9% accuracy	?
G-M Warren, Mich.	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
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 flouresce.	MIC

Unknown	Automated inspection of glass CRT Necks, uses a UV light source to image internal defects. Checks integrity 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 seminconductor photomask inspection for products.	?
Delco Electronics Kokomo, Indiana	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
G-M: General Motors
MIC: Machine Intelligence Corp.
RVS: Robot Vision System
? : Vendor of system not specified in literature