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# Robotic Realities: Near Term Prospects and Problems

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# Robotic Realities: Near-Term Prospects and Problems

*By* ROBERT U. AYRES and STEVEN M. MILLER

ABSTRACT: Industrial robots are automation, but with a difference. Other machine tools are extensions of human capabilities, while robots are seen mainly as substitutes for human workers. Robots will find most of their industrial applications during the next decade or two in the metalworking sectors, where they will begin to displace semiskilled machine operatives in medium to large batch production operations. They cannot substitute for skilled machinists or other workers doing nonroutine jobs, or specialized, dedicated hard automation used in mass production. The current generation of robots, lacking sensory data processing and interpretation capabilities, can potentially replace up to 1.3 million manufacturing jobs. The next generation, with crude vision or tactile senses; will potentially displace about 3 million more. However, only relatively large firms can profitably utilize many robots at present; it may be 20 years or more before these usage rates are achieved in practice. A shift from stand-alone machine tools, to manufacturing cells consisting of several machine tools served by a robot and controlled by a computer, will accelerate the practical use of robots in the 1990s.

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NOTE: This article is based largely on material that has been previously published. Major sources include Robert U. Ayres and Steven M. Miller, *Robotics: Applications and Social Implications* (Cambridge, MA: Ballinger, 1983); idem., "Robotics and Conservation of Human Resources," *Technology and Society,* 4(3):181-97 (Winter 1982); idem., "Socio-Economic Impacts of Industrial Robotics: An Overview," in *Handbook of Industrial Robotics,* ed. Shimon Y. Nof (New York: John Wiley & Sons, Inc., 1984, forthcoming). Reprinted by permission.

INDUSTRIAL robots are machine tools. In December 1982 there were about 33,000 in use worldwide, nearly 60 percent of them in Japan. About 7000 robots were in U.S. factories. Robots are not human-like androids that can walk around and converse, as in literature and films. Most of them are permanently fixed in one location. More realistically they are programmable manipulators that can move parts or tools through a prespecified sequence of motions. They are also—at present—crude, clumsy, blind for the most part, and very stupid. They usually have one arm and several steel fingers with a total of four, five, six, or at most seven degrees of freedom. Reprogrammability means only that the robot's actions can be modified by changing control settings, without changing the hardware. Robots combine some attributes of traditional machine tools as well as of machine operators. Like a machine tool they can repeat the same task for prolonged periods with great precision. By definition a robot must be flexible enough to be taught to do a new task, and to use accessory tools to extend its range of physical capabilities. The following is the classification of robots used in Japan; the first two categories in this Japan Industrial Robot Association (JIRA) classification are not currently defined as robots in the United States.[1]

1. Manual manipulator. A manipulator that is directly operated by a man.
2. Fixed sequence—pick and place—robot. A manipulator that performs a sequence of steps specified by means of cams, mechanically set limit switches, or hydraulic or pneumatic valves.
3. Variable sequence robot. A manipulator as defined in item 2, for which instructions can be specified by resetting electrical connections.
4. Playback robot. A manipulator that can remember and repeat any operation after being instructed by an operator; subcategories are known as walkthrough and leadthrough.
5. Numerically controlled (NC) robot. A manipulator that can receive instructions in digital form via magnetic tape or directly from a computer.
6. Intelligent robot. A robot that can modify its own actions in response to data obtained through its sensing and recognitive abilities.

Robots are utilized in industry for the usual virtues of machines: strength, speed, precision, untiring availability, predictability, reliability, and relative imperviousness to hostile environments. They do not as yet possess several important natural human capabilities: the ability to react to unforeseen circumstances or changing environments, and the ability to improve performance based on prior experience.

Thus, while robots are classed as flexible automation, this characterization is relative. Robots at present are flexible only in the limited sense that a programmed sequence of actions can be altered without actually rebuilding the device. For the crudest devices—types 1, 2, and 3—the reprogramming is actually done manually, by resetting switches or valves. For playback robots, type 4, the reprogramming is normally done by physically moving the robot arm through the desired sequence of motions. In the case of NC robots, type 5, instructions are digitized and read electronically from a magnetic tape or via some communications interface, from an external con-

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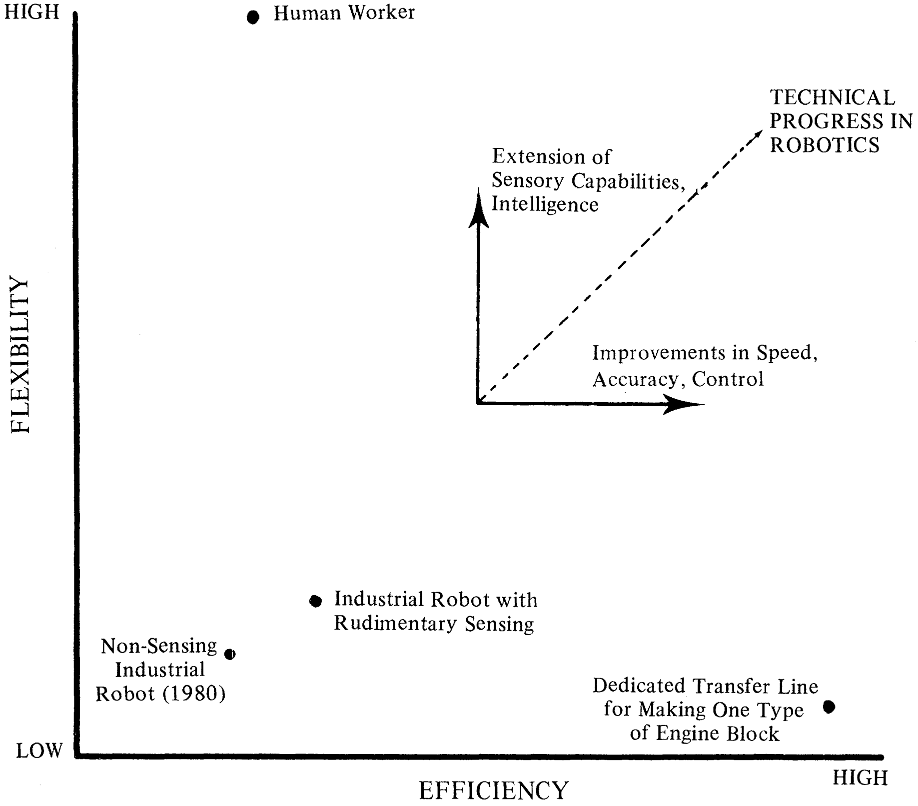
[1] JIRA, *The Robotics Industry in Japan: Today and Tomorrow* (Englewood Cliffs, NJ: Prentice-Hall, 1982).

FIGURE 1
THE RELATIVE FLEXIBILITY AND EFFICIENCY OF ROBOTS, HUMANS, AND SPECIALIZED MACHINES



troller-computer. State-of-the-art robots, type 6—mostly in research labs—do have crude senses of sight and touch, and limited capability to coordinate their manipulators with sensory input. Instructions must be provided externally, however, by a programmer.

Robots are flexible only when compared to so-called hard automation. They are not as yet particularly good at adjusting to varying conditions and unpredictable circumstances, as human workers can. Roughly the flexibility of humans is derived from a combination of high order sensory capability—vision, touch—and problem-solving ability—intelligence. On the other hand the purely mechanical attributes—strength, speed, precision—that robots share with other machines can be termed dexterity. Not surprisingly, while humans far exceed robots in sensitivity and intelligence, they lag somewhat in dexterity, as Figure 1 suggests qualitatively. Apparently biological organisms use intelligence and sensitivity to compensate for the inherent limitations of organic materials. Essentially the tasks robots can do better than humans are those requiring more dexterity than flexibility.

Because of current limitations, today's robots are usefully employed in highly structured industrial environments where practically all of the variability and decision making can be engineered out of the workplace. Existing uses of industrial robots all involve repetitive preprogrammable tasks such as spot welding, spray painting, palletizing, and the loading and unloading of metal forming, metal cutting, and other types of machines. The next generation of sensory-based robots will be able to perform a broader range of tasks under less structured conditions, in addition to becoming cheaper and easier to use. Expected uses of robots with vision and improved feedback control will include inspection, assembly, heat treatment, grinding and buffing, and electroplating. Capabilities of commercially available robots, and capabilities under development for future robots are listed in Table 1.

Eventually many of the hands-on tasks performed by production workers on the factory floor will be done by robots in computer controlled manufacturing systems. Programmable automation is beginning to replace the current generation of manually controlled machines. This transition will undoubtedly continue for many decades. There is potential for significantly improving the productivity of the manufacturing sector and increasing the wealth-producing potential of the economy as a whole. We also face significant social impacts, such as the short-term prospects of technological displacement, and the longer-term prospects of basic structural shifts in the economy.

## APPLICATIONS OF INDUSTRIAL ROBOTS

Specific tasks for which robots are used today are shown in Table 2. Experimental and future applications are also suggested. A summary characterization of benefits is shown in Table 3. Robots are not really cost-effective in most custom manufacturing applications, because in such cases a large fraction of the labor time is spent setting up the machines. Since each job is unique the setup requires the active involvement of a skilled machinist. For one-of-a-kind— prototype— or few-of-a-kind products, it is easier for a skilled machinist simply to make the piece than to figure out how to teach a robot or program an NC machine to do it. Thus custom production generally requires skilled workers and relatively inexpensive, manually operated, general purpose, single-spindle machine tools. All operations are carried out sequentially.

Robots are not generally cost-effective in mass production applications either, because specialized mass production machinery can usually perform the operations more efficiently than general purpose NC machines. Mass production machinery, or hard automation, is ultraspecialized to repeat a fixed sequence of operations at high speed for very long periods of time. Many operations are carried out in parallel on specially designed and dedicated transfer machines, perhaps with 100 or more tools—for example, drills—cutting simultaneously. Auto engines and transmissions are manufactured in this way. It is always difficult and expensive if not impossible to reconfigure the hard automated system for another product. It is usually cheaper to scrap the specialized

TABLE 1
**ROBOT CAPABILITIES**

| | Commercially Available Capabilities (1980) | Capabilities Sought for the Future |
|---|---|---|
| Learning | on-line programming via teach/playback modes<br>teaching in multiple coordinates<br>local and library memories of any size | general purpose robot programming languages<br>off-line programming<br>learning with experience |
| Decision making | program selection by random stimuli | world model of working environmental |
| Sensing | computer interpretation of sensory data<br>computer interfacing<br>two-dimensional vision with binary recognition<br>force/torque sensing<br>limited speech input | positional sensing<br>three-dimensional vision with gray levels and color<br>tactile sensing<br>voice communication<br>improved processing of sensory inputs<br>coordination of multiple sensory inputs and control |
| Manipulation | six infinitely controllable articulations between base and gripper<br>point to point control<br>continuous path control<br>position accuracy repeatable to 0.3 millimeters<br>handles up to 150 kilos | miniature manipulators<br>greater position accuracy<br>greater dynamic control<br>general purpose hands<br>multiple hand-to-hand coordination |
| Mobility | synchronization with moving workpieces | programmable omni-directional mobile bases<br>self-navigating mobile bases<br>walking robots |
| Reliability | 400 hours for mean time between failures | self-diagnostic fault tracing |

SOURCE: Adapted from Joseph F. Engelberger, *Robotics in Practice* (New York: American Management Association, 1980); see also Robert U. Ayres and Steven M. Miller, "Industrial Robots on the Line," *Technology Review*, 85(4):35-46 (May-June 1982).

machinery and to build a new system from scratch.

Between the two extremes—custom and mass—lies the domain of batch production, where NC machine tools and robots are particularly appropriate. It may be noted that very complex assemblies with many parts tend to be

TABLE 2
**ROBOT APPLICATION AREAS**

| Commercially Available Robots | Experimental Robots | Future Robots |
|---|---|---|
| Die casting | Assembly: | Exploration and extraction of materials: |
| Spot welding | electromechanical | |
| Arc welding | | in subsurface mines |
| Investment casting | insertion of other small fragile components | |
| Forging | | underseas |
| Press work | | |
| Spray painting | Inspection: | Satellite repair |
| Glass manufacturing | of electromechanical parts and assemblies | |
| Plastic molding | | Space manufacturing |
| Foundry work | of electronics parts and assemblies | |
| Machine tool loading | | |
| Heat treatment | | |
| Deburring of metal parts | Sheep shearing | |
| Palletizing | | |
| Brick making | | |
| Dimensional inspection | | |

produced in smaller batches than simpler items.[2] The typical relationship between the number of different parts made in a factory and output rate or batch size for each part is shown schematically in Figure 2.

For custom and small batch production, the cost of a product is predominantly attributable to labor, and unit costs do not decline much with volume. As batch size increases, more advanced—for example, numerically controlled—machines can be justified, since programming costs and specialized tools and jigs can be spread over more units. But the labor content is lower and unit costs decline more rapidly with volume.

At still larger production volumes it is possible to justify still more labor-saving specialization, including the integration of one or more robots and several machine tools in a flexible—reprogrammable—computerized manufacturing cell as depicted in Figure 3. Capital costs are higher, but unit costs drop still faster. With true mass production the flexibility or reprogrammability is sacrificed in exchange for maximum output rates. Typical total cost versus quantity schedules are shown in Figure 4, and unit cost versus quantity is shown in Figure 5. Note that Figure 5 shows three overlapping regions, characterized by different basic production technologies, discussed previously.

Each of the three technologies is the cost-minimizing choice only within the volume range for which it is intended, and an inefficient choice outside its appropriate range. For a given product, unit cost would decrease regularly as output increases over a wide range of volumes if one considers the lower envelope of the long-run cost curve, where the

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[2] The automobile appears to be an exception to the rule but actually is not. The final product, however, is assembled in moderately small batches from simpler subassemblies—engine, transmission, wheels, full system, brakes, and so on—that are themselves mass produced.

TABLE 3
CHARACTERIZATION OF ROBOT BENEFITS

| | Current Industrial Robots | Experimental Industrial Robots | Future Robots |
|---|---|---|---|
| Areas of application | Highly structured manufacturing task | Variable manufacturing task | Subsurface<br>Undersea<br>Space |
| Description | General purpose machine tool with no sensing capabilities | General purpose machine tool with limited sensing and decision-making capabilities | Autonomous system guided by artificial intelligence |
| Benefit | Factor saving:<br>capital<br>material<br>labor | Factor saving:<br>capital<br>material | Resource extending |

optimal—cost minimizing—technology is used for each level of output.

About 90 percent of current robot users in the United States fall within the industries of the metalworking sector. As the name implies, these industries are engaged in the fabrication, finishing, or assembly of products from standard metal shapes, and from mechanical and electronic parts and subassemblies purchased mostly from other metalworking industries. The metalworking sector includes the following groups of industries, designated by standard industrial classification (SIC) codes.[3]

—34: fabricated metal products;

—35: machinery, except electrical machinery;

—36: electrical equipment and machinery; and

—37: transportation equipment.

These industries have been described by Thomas Vietorisz as "the bellwether of economic growth"[4] for an industrial society because they produce all of the tools and capital equipment used by all manufacturing industries and all other sectors of the economy. The metalworking sector is the locus within the industrial system where new technological knowledge is embodied in a physical form, especially as capital goods. Since capital goods play such a critical role in the creation of new products, processes, and wealth, the importance of this sector extends far beyond the number of people it directly employs.

Based on an analysis of unit processing cost and level of output, we have estimated the dominant mode of pro-

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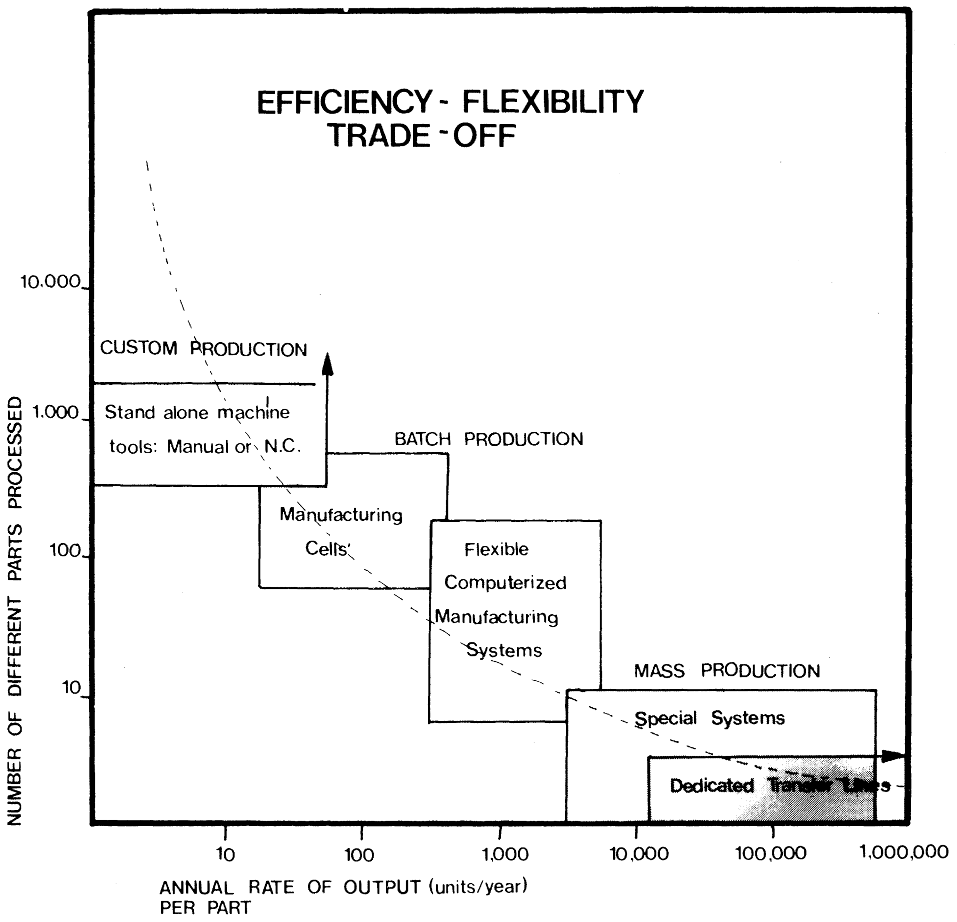
[3] This system of industrial classification has been developed over a period of many years under the guidance of the U.S. Department of Commerce. All data collected by the Bureau of the Census as part of the economic census, including the Census of Manufacturers, is organized according to the SIC system.

[4] *UNIDO Monographs on Industrial Development: Volume 4, Engineering Industry* (Vienna: U.N. Industrial Development Organization, 1969).

FIGURE 2



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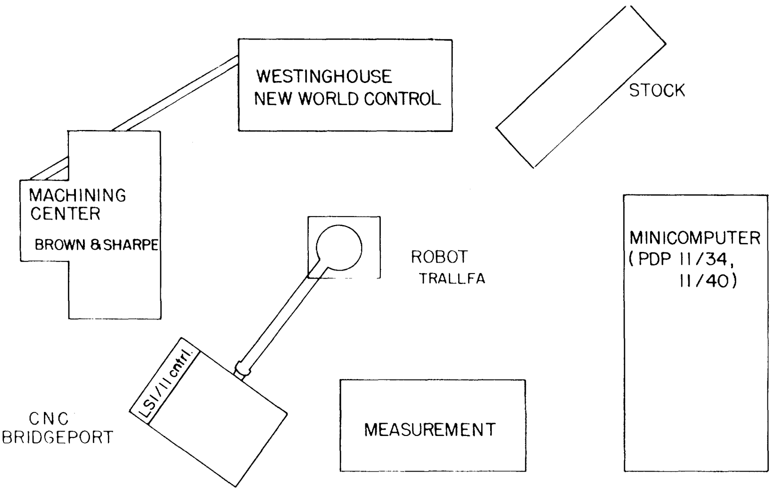
duction within 101 metalworking industries in SICs 34-37. Within this group the highest unit processing cost per unit output, measured in mass, is for SIC 3662, radio and television communication equipment, an extreme case of custom or very small batch production. The lowest unit processing cost is for SIC 3465, auto stampings, an extreme case of mass production. The range between these two extremes is a factor of 60. That is, SIC 3662 spends over 60 times as much as SIC 3465 in capital and labor cost per pound of material processed. Some of the unit cost differential between these two industries is due to differences in product complexity. However, if the unit processing cost of auto stampings is compared to that of an equally complex type of product that is custom produced such as nonferrous forgings, there is still a tenfold difference.

FIGURE 3
COMPUTER-ROBOT INTEGRATED MANUFACTURING CELL



As a rough generalization, for each 1 percent increase in the level of output, unit processing cost decreases by 0.38 percent for the metalworking industries in our sample. This implies that if a typical product were produced one-of-a-kind, unit processing cost would be 200 times greater than if it were mass produced at a million copies per year. If a typical product were produced in batches of 100 or 1000, unit processing cost will still be 35 to 15 times higher than if it were mass produced at a million copies per year. Clearly producers and consumers are paying a high premium for metal products produced in small batches.

We estimate that mass production industries account for about one-quarter of the value added, and about one-third of the total output in the metalworking sector. This suggests that much of the value added can be thought of as the cost of flexibility needed for product differentiation and specialization.

There are a limited number of robot applications in manufacturing sectors other than metalworking, though at present the problems associated with processing nonrigid or delicate materials, and with very high-speed production lines, restrict their use. Current and near-term future applications of robotics in the processing of leather, rubber, asbestos, plastics, and food, and in the manufacturing of glass, clothing, and wood products are briefly reviewed in R. D. Schraft, E. Schults, and P. Nicolaisen.[5] In both Japan and the United States demand for robots in the nonmanufacturing sectors of the economy currently account for a negligible part of the total market.

## POTENTIAL IMPACTS ON LABOR COST

Existing and likely near-term capabilities of robots make them candidates

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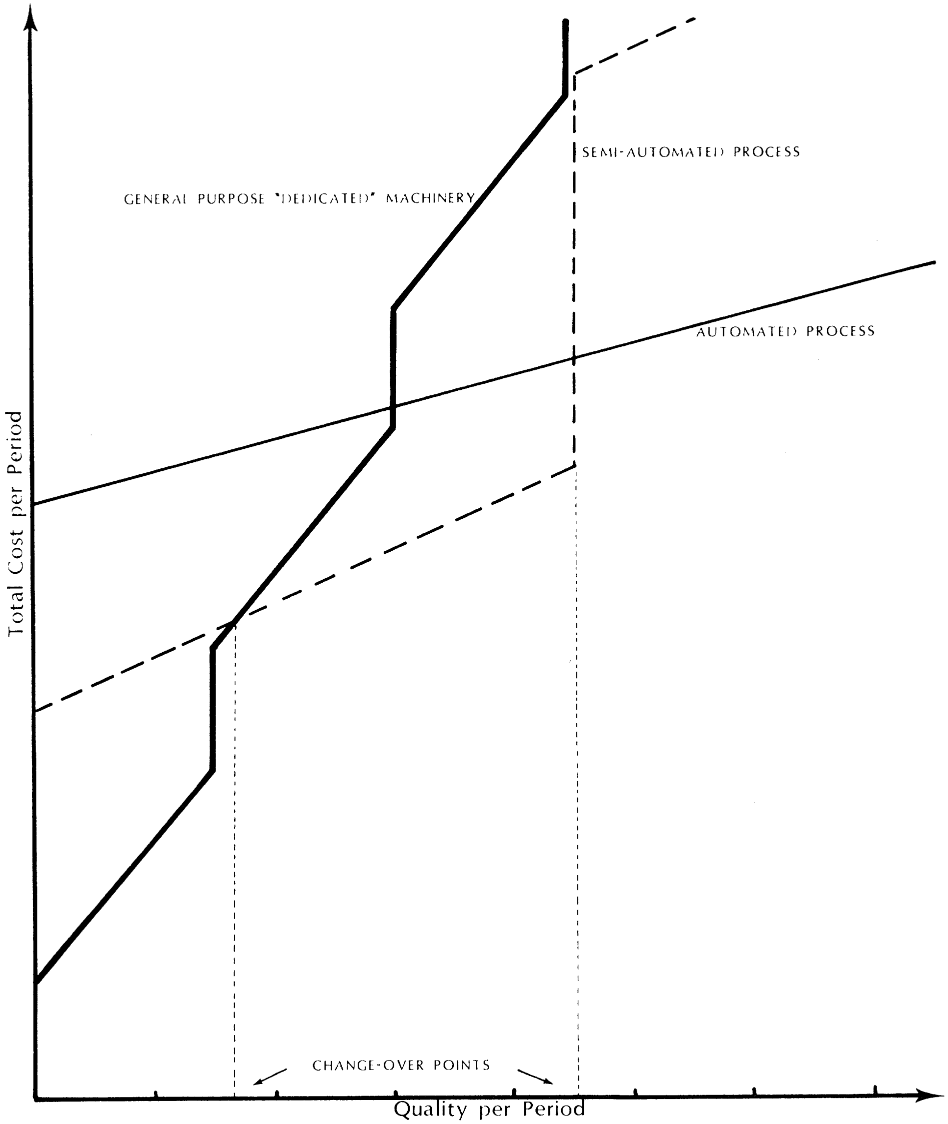
[5] "Possibilities and Limits for the Application of Industrial Robots in New Fields," in *Tenth International Symposium on Industrial Robots, Milan* (Bedford, England: IFS Publications, 1980).

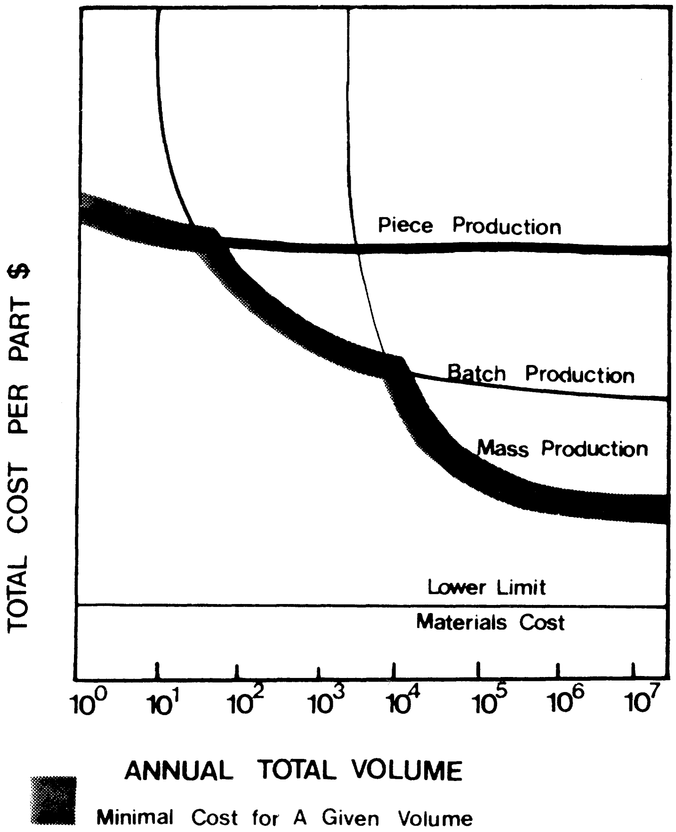
FIGURE 4
TOTAL COST VERSUS QUALITY SCHEDULES FOR THE MANUFACTURE OF A PARTICULAR PART BY DIFFERENT PROCESSES



to replace significant numbers of machine operators and unskilled laborers over the next three decades or so. In general terms the replacement of several million production workers by robots will decrease direct labor input. Consequently output per labor hour will most certainly increase, although the effects on total factor productivity depend on the requirements for new capital and other ways in which robotic—and computer aided design/computer aided manufacturing (CAD/CAM)—technology may alter production technology.

Within the metalworking industries, where robots seem to be most applica-

FIGURE 5
UNIT COST VERSUS QUANTITY



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ble, direct wage and benefit payments to production workers comprise less than 18 percent of the total value of output on average. The true labor cost is actually the sum of direct labor cost plus the labor cost embodied in the purchased materials. However, only direct labor costs are relevant to technology choice. Hence for now we consider an industry in isolation, without considering the effects of cost savings that might be passed on to customers.

Potential reductions in production labor is based on three scenarios, outlined in Table 4. Fabrication workers include all types of skilled and semiskilled machine operators and setup workers, as well as material handlers, laborers, and miscellaneous types of skilled, semiskilled, and unskilled production workers. It is assumed that maintenance workers will not be replaced. The low scenario represents the current potential for replacing factory workers with insensate robots. The medium scenario represents the near-term potential for replacing factory workers with the emerging generation of

TABLE 4
**REPLACEMENT SCENARIOS**

| Occupation | Percentage Replaced<br>Low | <br>Medium | <br>High |
|---|---|---|---|
| Fabrication workers | 20 | 50 | 75 |
| Assembly workers | 0 | 25 | 75 |
| Inspectors | 0 | 0 | 75 |
| Supervisors | 0 | 0 | 75 |

sensor-based robots. From a technical standpoint these two scenarios could be realized within the decade. The high scenario is our own subjective estimate of the long-term potential for eliminating production labor in the millenial factory of the future.

In the low- and medium-replacement scenarios, the potential direct cost reductions—not counting pass-through effects from suppliers—appear to be modest, averaging near 2 percent and 5 percent, respectively. The potential cost reduction is greater in the high-replacement scenario, averaging about 14 percent. Of course, the upper limit on potential cost savings from eliminating production workers is given by the total production worker portion of output in the near term, considering the low- and medium-replacement scenarios. It does not appear that the direct substitution of robots for factory workers by itself would have a substantial impact on total cost even in those industries where robot use is most heavily concentrated. Something else must happen if large savings in cost and increases in productivity are to be realized in the near term.

## POTENTIAL IMPACTS ON CAPACITY

Possibly more significant is the impact of robotization and CAM on factory organization and utilization of machinery and equipment. Throughout the major metalworking industries there are on average more machines than operators. The actual ratio of machines to operators understates this point, since each machine is available three shifts per day, whereas an operator only works a single shift, or slightly longer, allowing for overtime. Comparing the total hours worked by machine operators to the total hours machines are available, it is clear that on average machines are operated only for a small portion of the total time they are available. According to our estimates in Table 5 the effective utilization of manually operated metal cutting and metal forming machines and welding equipment is remarkably low.

The average figures are 13 percent, 14 percent, and 21 percent, respectively, assuming that theoretical utilization corresponds to 24 hours per day, seven days a week, with one operator per machine. On average, NC metal cutting machines are utilized more fully than manually controlled cutting and forming machines. However, in 1977 fewer than 3 percent of the metal cutting machines were NC. These estimates measure only the proportion of time an operator is available to run the machine, with no allowance for the possibility that the machine may be idle part of the time when the operator is on duty. Produc-

## TABLE 5
## ESTIMATES OF AVERAGE MACHINE TOOL UTILIZATION IN THE METALWORKING INDUSTRIES, 1977*

| Major Group (SIC) | Machine Type (percentages)<br>Metal Cutting, Manual | Metal Cutting, Numerically Controlled | Metal Forming | Joining—Welding | All Machines, Average |
|---|---|---|---|---|---|
| 34 | 12.4 | 18.4 | 15.8 | 15.1 | 14 |
| 35 | 12.7 | 20.9 | 7.4 | 17.8 | 13 |
| 36 | 9.9 | 29.3 | 13.0 | 8.2 | 11 |
| 37 | 16.5 | 14.8 | 17.5 | 40.0 | 20 |
| Average | 12.9 | 20.0 | 13.6 | 21.3 | 14 |

SOURCES: Machine tool hours derived from "The Twelfth American Machinist Inventory of Metalworking Equipment, 1976-78," *American Machinist*, 122(12):133-48 (Dec. 1978); labor hours derived from Bureau of Labor Statistics, *Occupational Employment in Manufacturing Industries, 1977* (Washington, DC: Government Printing Office, 1980).

*Machine utilization is defined here as follows:

$$\text{utilization} = \frac{\text{total operator hours available}}{\text{total machine hours available}}$$

total operator hours available = (number of operators) × (average hours worked per operator per year)

$$\text{average hours worked per operator per year} = \frac{\text{total hours worked by production workers}}{\text{total production workers}}$$

total machine hours available = (number of machines) × (8760 hours per year)

8760 hours per year = (24 hours per day) × (365 days per year)

tive cutting time by machine tools as a fraction of theoretical capacity in low- and medium-volume shops is 6 percent and 8 percent, respectively, increasing to 22 percent for high-volume, mass production operations.

Thus it is clear that most machines, especially in the metal working industries, are idle most of the time, even before making allowances for setup time, load/unload time, and other adjustments. Even in the most automated industries, such as the production of automobile engines and transmissions, true machine tool utilization rates as high as 50 percent are seldom if ever achieved. We believe the major quantifiable economic impact of robotics and CAM will be to expand sharply the effective capacity of production facilities by increasing both the amount of time per year the plant is operating and the throughput per shift. Much of the lost time is due to incomplete use of the second and third shifts and to plant closings for holidays, strikes, and other reasons. Weekends, holidays, and night shifts are less popular than the normal 40-hour work week. Consequently even if labor is available during these periods, it is more expensive.

Under normal operating conditions in a healthy economy even high-volume plants are shut down nearly 80 days per year due to Sundays, holidays, and planned closings for retooling. Mid-volume plants are closed on average 102 days—all weekends—and low-volume plants are closed nearly 125 days out of the year—weekends plus three weeks for

## TABLE 6
## POTENTIAL PERCENTAGE INCREASES IN OUTPUT FROM UTILIZING LOST TIME

| Type of Plant | From Utilizing Days Plant Is Closed | From Utilizing Nonscheduled Production Time | Total Increase in Output |
|---|---|---|---|
| High-volume | 28 | 3 | 31 |
| Mid-volume | 83 | 115 | 198 |
| Low-volume, one-shift operation | 148 | 187 | 335 |
| Low-volume, two-shift operation | 74 | 43 | 117 |

SOURCE: Corrected from Robert U. Ayres and Steven M. Miller, *Robotics: Applications and Social Implications* (Cambridge, MA: Ballinger, 1983); see also Steven M. Miller, "Potential Impacts of Robotics on Manufacturing Cost within Metalworking Industries" (Ph.D. diss., Carnegie-Mellon University, 1983).

holidays and shutdown. When open for production, high-volume plants are typically operating over 22 hours per day, whereas mid-volume and low-volume plants are typically scheduled to operate 10.7 and 8 hours per day respectively. Clearly there is considerable potential for increasing output, and thereby decreasing unit cost, by saving long runs for an unmanned third shift or weekend, using robot operators. During the next two decades, as manufacturers gain experience with unmanned factory operations, the less routine machine setup, repair, maintenance, and inspection tasks could be reserved for the regular day shift. Planned shutdowns required for retooling would be substantially reduced, or possibly eliminated in a robot-integrated factory with flexible production technologies.

A summary of the potential for increasing available production time, hence output, in existing facilities is shown in Table 6. Output per year could be increased by perhaps 30 percent in high-volume plants, and by at most 200 percent in mid-volume plants. If low-volume plants are operating only one shift per day, recouping cost time could increase output by over 330 percent. If we generously assume that low-volume shops are operating on a two-shift basis—which only a portion do—output per year could still be increased by nearly 120 percent.

In addition to extending the amount of working time per year, robotics, especially when integrated with other CAM technologies, can increase capacity by increasing the number of parts produced per hour. As we have seen in Table 5, machines are productively engaged only about 30 percent of the time the plant is open and operating. The remaining 70 percent of possible production time is lost for a variety of reasons. Recouping the fraction of possible production time that is lost to nonproductive uses would further increase the effective capacity of machine tools.

Much of the lost time is machine related: equipment limitations, tool changing, and equipment failures. However, a sizable fraction of time lost is due to management and work force practices, including personal time breaks, late starts, early quits, material handling, excessive machine adjustments, and in-line storage losses due to scheduling inefficiencies. Personal time, late starts, early quits, and some fraction of the material handling time could be virtually eliminated by replacing workers with robots. Time losses due to tool changing, equipment failures, excessive machine adjustments, setups, and scheduling inefficiencies will probably not be affected directly by robots, but might be reduced if more aspects of factory work were consolidated and controlled by sensor-based computer systems. For example, sensors monitoring machine performance would eliminate unnecessary adjustments and speed up diagnosis of machine failures.[6] If stand-alone machines were replaced by a flexible manufacturing system, and if parts processing were rationalized by adopting group technology, there would be less material handling and the scheduling of parts and tools would be simplified. Even a substantial fraction of the equipment-related losses could be eliminated in a fully integrated flexible manufacturing system, since the whole system need not be stopped if one station malfunctions. Robots or programmable pallets under the control of a central scheduling computer could reroute parts to other work stations.

It is difficult to discuss the potential improvements in productivity that may be brought about by robotics in isolation from the development of CAM systems and other forms of factory automation. Retrofitting robots into existing production lines will bring about some improvements, such as improving the utilization of a single machine or work station, but we do not expect that it would dramatically improve overall factory performance. Substantial effects on factory performance and costs require the integration of robots and other forms of factory automation into coordinated manufacturing systems. It also becomes more difficult and less meaningful to distinguish between robots and other forms of factory automation as the concept of robotics evolves from programmable manipulators to machines and systems that can "sense, think and act."[7]

Our rough estimates of potential increases in throughput that could be achieved from recouping the nonproductive time lost during scheduled operations are based on informed judgments, but have been reviewed by several industry experts. They are not the result of detailed analysis. We distinguish two levels of improvements as a result of (1) uses of robots per se, and (2) integrating robots with CAM systems and other forms of factory automation. We suggest that the installation of robots, without increasing the time normally planned for operations and without extensively adding other forms of automation, would result in a 10 percent increase in

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[6] In the next few years time lost to equipment failure could conceivably increase as systems become more automated and more complex. However, over the next two decades we expect improvements in machine reliability and sensor-based diagnostic systems to improve machine and system reliability and to reduce equipment failures.

[7] We borrow the broader definition of robotics as machines that can "sense, think and act" from Raj Reddy, director of the Carnegie-Mellon Robotics Institute.

### TABLE 7

### POTENTIAL PERCENTAGE OUTPUT INCREASES FROM WORKING MORE EFFICIENTLY DURING PLANNED OPERATIONS: MID-VOLUME MANUFACTURING

| Function | Percentage of Operating Time | Potential Percentage Reduction | Adjusted Percentage | Potential Percentage Reduction | Adjusted Percentage |
|---|---|---|---|---|---|
| | | (robots only) | | (robots with CAM) | |
| Setup and gauging | 22 | –30 | 15.4 | –65 | 7.7 |
| Load/unload and noncutting | 12 | –40 | 7.2 | –60 | 4.2 |
| Tool change | 22 | –5 | 20.9 | –15 | 18.7 |
| Equipment failure | 7 | 0 | 7 | 0 | 7 |
| Idle time | 12 | 0 | 12 | –25 | 9 |
| Productive fraction | 25 | 0 | 25 | 0 | 25 |
| Total scheduled production time | 100 | | 87.5 | | 64.6 |
| Output index | 1.0 | | 1.14 | | 1.55 |

SOURCE: Breakdown of operating time from John E. Mayer and David Lee, "Estimated Requirements for Machine Tools during the 1980-1990 Period," in *Machine Tool Systems, Management and Utilization,* ed. Arthur R. Thompson (Lawrence, CA: Lawrence Livermore National Laboratory, 1980), vol. 2 of *Machine Task Force Report on the Technology of Machine Tools,* pp. 31-41; estimates of potential reductions from Ayres and Miller, *Robotics: Applications.*

output in high-volume machining operations—not including assembly—and nearly a 15 percent increase in output in mid-volume and low-volume production. If robots were used in conjunction with other forms of factory automation, still without increasing the number of hours normally planned for operations, output might be increased by nearly 50 percent in mid- and low-volume production, and possibly by 40 percent in high-volume production. A breakdown of the mid-volume case is shown in Table 7.

Our judgments regarding the estimated improvements, as in Table 7, are mostly applicable to situations of retrofitting or incrementally adding technologies within existing plants. Other studies suggest that completely redesigning the factory around new technology could result in substantially greater improvements in throughput during planned production periods. For example, John E. Mayer and David Lee[8] of Ford Motor Company estimated the combined effects of applying the most advanced concepts to almost all aspects of machine design and control and factory layout in high-volume machining systems. They considered the use of automatic loading/unloading, automatic tool changing, diagnostic sensing, component reliability, and unmanned operation, as well as improved line balancing and faster cutting speeds. Their results suggest that all of these improvements, without increasing cutting speeds, could result in a 90 percent increase in output. If cutting speeds were increased to their upper lim-

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[8] "Estimated Requirements for Machine Tools during the 1980-1990 Period," in *Machine Tool Systems, Management and Utilization,* ed. Arthur R. Thompson (Lawrence, CA: Lawrence Livermore National Laboratory, 1980), vol. 2 of *Machine Tool Task Force Report on the Technology of Machine Tools,* pp. 31-41.

TABLE 8
**SUMMARY OF POTENTIAL INCREASES IN CAPACITY**

| Type of Plant | Base Case | Potential Capacity Increases<br>Robots Only | <br>Robots with CAM |
|---|---|---|---|
| High-volume | | | |
| Available hour index | 1.00 | 1.31 | 1.31 |
| Throughput index | 1.00 | 1.11 | 1.39 |
| Output index | 1.00 | 1.45 | 1.82 |
| Increase in output (percentage) | | 45 | 82 |
| Decrease in unit cost (percentage)* | | –13 | –21 |
| Mid-volume | | | |
| Available hour index | 1.00 | 2.98 | 2.98 |
| Throughput index | 1.00 | 1.14 | 1.55 |
| Output index | 1.00 | 3.40 | 4.62 |
| Increase in output (percentage) | | 240 | 362 |
| Decrease in unit cost (percentage)* | | –37 | –44 |
| Low-volume, single shift | | | |
| Available hour index | 1.00 | 4.35 | 4.35 |
| Throughput index | 1.00 | 1.16 | 1.52 |
| Output index | 1.00 | 5.05 | 6.61 |
| Increase in output (percentage) | | 405 | 561 |
| Decrease in unit cost (percentage)* | | –46 | –51 |
| Low-volume, double shift | | | |
| Available hour index | 1.00 | 2.17 | 2.17 |
| Throughput index | 1.00 | 1.16 | 1.52 |
| Output index | 1.00 | 2.52 | 3.30 |
| Increase in output (percentage) | | 152 | 230 |
| Decrease in unit cost (percentage)* | | 30 | 37 |

*Assuming that the elasticity of unit cost with respect to output is –0.388, based on econometric analysis found in Miller, "Potential Impacts of Robotics."

its as well, over a 200 percent increase in output could be achieved. Their estimates are also based on current operating times—no changes in shifts per day or days per year.

The potential effects of utilizing nonscheduled production time and of recouping time lost to nonproductive uses during scheduled operations are combined in Table 8. To utilize all of the time normally not scheduled for production—plant shutdowns, holidays, Sundays—the plant would sometimes have to operate with skeleton crews, or even operate unmanned during some periods under the control of computer systems. Thus if we assume that hours available for production could be increased to the upper limit, we should consider the case of robots used in conjunction with other CAM technologies. For the robots-with-CAM case, high-volume machining operations show a potential output increase of 80 percent. Mid-volume manufacturing, and low-volume producers already on a double shift show a potential output increase of 360 percent and 230 percent, respectively. For low-volume producers operating on normal single shifts, the potential increase is 560 percent. In mid- and low-volume manufacturing, potential increases in output are almost all the result of increasing planned production time. In high-volume machining operations, the contribution of increasing throughput per period is somewhat greater than the contribution of increasing hours planned for production.

Assuming that there is a market for additional goods, an increase in output can be viewed as a reduction in unit cost. Estimates of the percentage decrease in unit cost that would result from the percentage increases in output are given in Table 8. These are derived from a study documenting the extent to which unit cost tends to decrease as the level of output increases across metalworking industries.[9] In high-volume manufacturing, unit cost could be decreased by 13 to 20 percent by increasing output by the indicated amounts. Low-volume single-shift and mid-volume producers could reduce unit cost by 40 to 50 percent by increasing output by the indicated amounts.

For the sake of comparison in our discussion of the effects on labor costs earlier in this article, we noted that on average total cost would be reduced by roughly 2 percent if 20 percent of all fabrication workers were replaced, and by roughly 5 percent if 50 percent of all fabrication workers and 25 percent of all assemblers were replaced. Potential cost savings theoretically obtainable from increasing machine utilization appear to be roughly an order of magnitude larger than savings that could be realized by replacing production labor costs under the low- and medium-replacement scenarios. Even if almost all production labor costs were eliminated, the savings that could be realized in low- and mid-volume manufacturing by increasing output would be two to three times greater.

## INVENTORY AND WORK-IN-PROCESS COSTS

It has been estimated that in typical batch production operations only 5 percent of the throughput time is required for actual production—a workpiece spends 95 percent of the time in transit or in storage. This suggests that a piece requiring 10 hours of machining time would take at least 8 days and up to several weeks to pass through the factory. Improved work scheduling in combination with higher rates of machine utilization could dramatically reduce the time required to move work through the factory.

Inventories of work in process and finished goods on hand at the end of the year typically comprise between 10 and 30 percent of the value of shipments. Robotics and flexible manufacturing systems will not necessarily decrease the levels of inventory on hand. In fact they may require increased inventory levels, since higher levels of machine utilization will mean higher output rates, and it will be more important to keep a buffer supply of work always available to keep the machines busy.

The financial benefits of reducing the time it takes to move inventory through the plant can be seen from the following example. Suppose a shop with an average of $1 million annual revenues has a 100-day average lead time, which is not atypical. If that lag could be instantly cut to 10 days, the firm would be able to

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[9] Steven M. Miller, "Potential Impacts of Robotics on Manufacturing Cost within Metalworking Industries" (Ph.D. diss., Carnegie-Mellon University, 1983).

increase a total output for that year by 25 percent and put the next 90 days' revenue, $250,000, into the bank, without increasing costs at all. Deliveries would obviously be speeded up, to the benefit of customers. The added revenue would effectively be converted from unavailable working capital into liquid cash. The firm would also save significantly on out-of-pocket warehousing and other inventory-related costs.

### CAPITAL COSTS

In a general purpose batch production facility, capital equipment and labor are shared among a large number of products, since the requirements for a particular product are not large enough to tie up all available equipment. As discussed earlier, the flexibility of a job shop is achieved at the cost of reduced levels of equipment utilization. This can be thought of as capacity loss due to sharing. Increased machine utilization resulting from the adoption of robotics can be viewed as recouping some of the capacity that was lost as a result of capital sharing. In many instances increases in output would cut fixed cost per unit produced drastically, despite the added expenditures for the robots and the accompanying manufacturing systems. The other major effect of programmable automation on capital cost would be a reduction in the long lead times incurred in the sharing context, which would reduce some part of the inventory cost, as already mentioned.

The capital costs of a flexible manufacturing system at present are typically somewhat greater than for conventional types of automation.[10] Currently computer controlled flexible automation is expensive, primarily because of software costs. However, this differential might be reduced to some extent or even eliminated if such systems are built from relatively standardized elements, including programs, as opposed to being custom built, like most specialized production facilities of today.

In general, if capacity could be increased significantly, flexible manufacturing systems could reduce both fixed and variable costs of batch production per unit. Figure 5 shows how robotics and CAM promise to shift the existing average unit-cost curve envelope closer to the ultimate lower limit—materials cost—over much of the spectrum of the production rates, particularly the mid-to-high-volume range.

### THE CONSEQUENCES OF DRAMATIC IMPROVEMENTS

Suppose, as we suggest, that unit cost in batch and custom manufacturing could be reduced to below current levels, mostly as a result of expanding the capacity, and output, of existing facilities.[11] There are several consequences

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[10] However, the flexible manufacturing systems typically have a greater range of capabilities than the equipment it replaces. While overall capital cost might be higher, cost per unit of capability—if this could be measured—might well be lowered for the computer controlled flexible manufacturing system.

[11] Much of the savings could in principle be achieved without eliminating labor. However, the higher machine utilization rates can be achieved only by using computers and robots to control the flow of work within the whole factory, eliminating the need for much of the hands-on labor, which in turn eliminates worker-related slow-downs and bottlenecks. If capacity increases are achieved, it would be profitable to pay some of the current workers just to stay out of the way, in order for the machines to be more fully utilized. However, this is unlikely to be the most productive or socially

for employment, depending on how demand for the product changes as price declines. This relationship is given by a parameter referred to as a product's own price elasticity of demand, defined as the percentage increase in demand for a 1 percent decrease in price.[12] A distinction is usually drawn between three cases:

1. Inelastic. A 1 percent reduction in price leads to less than a 1 percent increase in quantity demanded. As a result price cuts decrease total revenue, and probably profits.
2. Unitary. A 1 percent reduction in price leads to a 1 percent increase in quantity demanded. Price cuts leave total revenue and profits unchanged.
3. Elastic. A 1 percent reduction in price leads to more than a 1 percent increase in quantity demanded. Price cuts result in an increase in total revenue and profits.

First, take the case of a relatively modest price cut. Suppose that firms within an industry retrofit robots into existing facilities. They realize a 10 percent decrease in production labor cost, and a 25 percent increase in throughput, at the cost of 5 percent increase in annual capital outlays. Based on these assumptions, labor requirements per unit of output would decrease from 1.0 to 0.72, a 28 percent decrease. Given this decrease in unit labor requirements, demand within this industry would have to increase by 39 percent—1.0/.72-1.0—to keep the same number of workers employed as before. To calculate the reductions in unit cost, which we assume are passed on as price cuts, we figure that the cost proportions in this industry are representative of several industries within the fabricated metals sector (SIC 34).[13] Assuming the improvements and costs mentioned before, this industry would realize a 21 percent reduction in unit cost. The price elasticity necessary to induce enough increase in demand to keep all the displaced people employed is given by

$$\frac{\text{39 percent increase in output}}{\text{21 percent decrease in price per unit}} = 1.85$$

In other words, for each 1 percent decrease in price, there would have to be a corresponding 1.86 percent increase in quantity demanded to generate enough additional employment so that displaced workers could remain within the industry. For the sake of comparison we note that the elasticity for household appliances has been estimated to be roughly 2.0, which makes it one of the most price responsive of all consumer goods. We would not expect capital goods or most other products of the metalworking industry to be as price responsive as consumer appliances.

Unitary elasticity of demand—with the percentage increase in quantity demanded equaling the percentage decrease in price—is the most reasonable assumption for most intermediate goods, lacking other data. Given a price elas-

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acceptable use of human resources. It also depends on being able to sell the additional output.

[12] The demand for a product depends on its own price, as well as on the price of other products that could be used as substitutes. In the discussion we assume that only the price of the product in question is varying, and that prices of other products and of other important variables, such as income levels, remain constant.

[13] We assume the following cost proportions: production labor cost equals 23 percent of value of shipments, nonproduction labor cost equals 7 percent, capital cost equals 20 percent, and materials cost equals 50 percent.

ticity of unity, a 21 percent reduction in price per unit would induce a 21 percent increase in output with no change in revenues. With the reduced unit labor requirements, as before, this outcome would still leave 13 percent of the workers previously employed in the industry displaced.[14] Demand for some consumer tools, including automobiles and appliances, is more dependent on price. If the price elasticity of automobiles were 2, a 21 percent reduction in price or cost would induce a 42 percent increase in sales. Even with the reduced unit labor requirements as given before, this would yield a 2 percent increase in employment requirements and produce additional revenue and profits for the manufacturers as well.

Robot use could easily result in more dramatic reduction, both in unit labor requirements and in prices.[15] Suppose all producers within an industry were to refurbish their existing facilities completely, or even build new plants. For the sake of discussion let us assume that the new facilities realized a 20 percent reduction in production labor cost and achieved a 100 percent increase in output, at the expense of a 20 percent increase in annual capital outlays. In this case unit production cost would drop by 50 percent. With the reduced unit labor requirements, output would have to expand by 250 percent to create enough work to keep all the displaced workers employed in the same industry, which would require a very high price elasticity of 5. If demand increased only by as much as prices decreased, 50 percent, the employment of production workers would drop 40 percent from previous levels.

These examples suggest that if robotic technologies were to be widely used, not all displaced workers could be expected to be reemployed in their current industries, as a result of price reductions and increased demand. The effects of price reductions on demand, and the net employment effect, balancing job displacement and job creation, will vary considerably among the various metalworking industries, depending on the nature of the product and its market. The logical conclusion is that employment of production workers in most manufacturing industries will decrease, despite substantial improvements in productivity within these industries and possible increases in production.

This does not mean, however, that total employment in the economy as a whole would decrease. Substantial reductions in prices of intermediate and capital goods—for example, 20 percent in the first example, and 50 percent in the second—should reduce the cost of manufacturing consumer goods, and of creating new goods and services, both of which will increase the consumer's real buying power. This will in turn stimulate effective demand for other goods and services which should create new employment opportunities.

The foregoing analysis assumed that the only way to utilize the extra capacity made available by robotic systems was to increase the output of the goods that are already produced in that factory or

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[14] 0.72 labor units/unit of output × 1.2 units of output = 0.87 units of labor = a 13 percent decrease from the base case.

[15] As an aside, if demand were to increase by several hundred percent—and in some cases it might—many established organizations would not be prepared to cope with the increased complexity of organizing their business. It would strain the organizational structure, especially information processing capabilities. As a result producers sometimes purposely restrain their technological capabilities in order to keep their business manageable.

industry. However, there is an option of making greater use of the expanded capabilities and of the flexibility of robotic production systems to produce a wider range of products, and to manufacture new, high-performance products. Thus simply looking at the price elasticity of demand for current products might substantially underestimate the extent to which additional flexible capacity could be utilized. If the benefits of robotics and other types of programmable manufacturing technologies are to be fully exploited, there needs to be a concurrent emphasis on the development of new products to utilize the expanded capabilities. A new strategy that places much more emphasis on product performance, and less on standardization and cost reduction, might require an abrupt shift in many existing corporate strategies.

To summarize, the primary economic benefit of robotics is likely to be a reduction in the real cost of manufacturing products made in small-to-medium batches. Capital goods, machine tools, and the other types of durable equipment, as well as the parts used in them, are largely batch produced.[16] Thus the price of capital goods in relation to final products can be expected to decline significantly over the next quarter-century. This will cause secondary ripple effects in the prices of other manufactured goods and services throughout the economy. This in turn will reduce the real price of final output of mass-produced consumer goods, as well as the real price of output of the nonmanufacturing sectors. Final demand would also be stimulated to some extent, depending on the sensitivity of final demand to price. For consumer goods, high price elasticities tend to be more the rule than the exception.

Lower production costs will also have a beneficial impact on the rate of inflation. Insofar as inflation is caused by too much money chasing too few goods, an increase in productivity is perhaps the best way to break out of the vicious cycle. Ultimately, such changes will also affect other important macroeconomic variables, including the overall level and composition of employment, and the level of distribution of income. These second-order effects, while less immediate, may have greater ultimate importance than the immediate improvements in labor productivity in manufacturing. It is beyond our present scope to attempt to forecast the detailed nature, magnitude, or time phasing of these broad economic impacts.

We expect that improved robots and substantial reductions in the price of intermediate and capital goods will play an important role in facilitating the development of several capital-intensive growth sectors in the economy, including hazardous waste management, biotechnology, undersea mineral extraction, and space manufacturing. These sectors would also provide employment. It is important to know whether or not the levels of economic growth required to absorb workers displaced by robotics and other technological changes can be achieved in the economy as now structured. If the required levels of economic growth, and employment, cannot be achieved as a result of cost saving improvements in the manufacturing process, resources may have to be reallocated to encourage the creation of new

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[16] The major exception is automobiles. Large appliances, such as refrigerators, air conditioners, and washing machines, are also mass produced durable goods, but since they are sold to consumers they are not classified as producers' durable equipment.

products or services, or the development of new frontiers, such as the oceans and space. This would require a reevaluation of traditional policies of stimulating economic growth by encouraging aggregate investment.

## EMPLOYMENT EFFECTS

The limited experience to date is consistent with the point of view that for the overall economy industrial robots pose little serious threat to employment in the coming decade. Assuming 1600 robots in use in the United States in 1977 and 6800 by the end of 1982, and assuming that each robot displaces two or three workers on average, robots may have displaced 3000 to 5000 workers by 1977 and up to 20,000 by the end of 1982. The last figure cited would represent about one-fifth of 1 percent of the approximately 9.7 million semiskilled operatives and unskilled laborers employed in manufacturing industries in the United States in 1980. From this perspective the effects of employment up to now have been negligible.

But extrapolating the experience of the recent past into the future overlooks the concentration of effects in a relatively narrow sectoral, occupational, and regional setting. In particular, robotization along with other and frequently related developments could diminish employment opportunities for semiskilled operatives and unskilled laborers in durable goods industries, especially in the metalworking sector. These considerations imply that the displacement will be of sufficient magnitude, at least in some industries and regions and for some groups of workers, to be a cause for concern.

Robots and CAM continue the long-term trend toward mechanization and computerization that have made for relatively static employment in manufacturing industries in the United States, despite increased output. The significance of robotization in the next decade or two is that it will add to the combination of factors that have retarded growth in manufacturing employment. The percentage of the work force employed in industry—mining, manufacturing, and construction—has steadily declined from about one-third of the work force in 1959 to barely one-quarter in 1977. Projections by the Bureau of Labor Statistics indicate that this trend will continue. In addition the service content of each major sector of the economy, as represented by the proportion of the industry work force classified as nonproduction workers, has steadily increased. In 1980 over one-quarter of the employees in manufacturing and mining were performing managerial, professional, clerical, sales, or supervisory activities.

In 1980 about 14 million people were employed as production workers in manufacturing. Nearly half of all production workers, and nearly half of all manufacturing workers, are concentrated in the metalworking industries. Manufacturing production workers are classified into three main categories: craft—skilled workers; operative—semiskilled workers; and laborers—unskilled workers. Most of the routine repetitive jobs that currently lend themselves to automation and robotization are performed by these semiskilled nontransport operatives, who comprise nearly 40 percent of total manufacturing employment. In several job categories that appear most amenable to robotization, almost all employment is concentrated in metalworking. For instance, nearly all the 1 million operatives of metal cutting and metal forming machines are employed in these industries.

While the majority of jobs that can be robotized are semiskilled operative jobs, there are already robot applications in heat treating, sheet metal work, and forge and hammer operations, which are classed as skilled jobs. As computer aided design and manufacturing become more integrated, and if factories are to exploit fully robotics and other types of programmable automation, a larger fraction of the so-called skilled metalworking crafts will be vulnerable to automation.

The technical potential for replacing workers by robots has been estimated from an analysis of industry employment by occupation and from survey responses to the potential for substitution within a given occupation. Two levels of robot technology are distinguished: robots similar to those on the market in 1981—Level I; and robots with rudimentary sensory capabilities—Level II. In 1980 there were nearly 6.7 million production workers employed in the metalworking sector in the United States. Of these, nearly 5 million worked within the three broad categories of jobs most amenable to robotization—metalworking craft workers, semiskilled machine operators, and laborers. Based on the survey results, we estimate that Level I robots could theoretically replace 16 percent of the workers in these three groups, and that Level II robots could theoretically replace 40 percent of the same population of workers. Thus, if all the potential for job displacement of Level I robots were realized in metalworking, more than 800,000 jobs could be eliminated. If Level II robots were available and fully exploited, an additional 1.2 million jobs, or a total of nearly 2 million jobs, could theoretically be eliminated.

Extrapolating the data for metalworking to similar tasks in other manufacturing sectors, it appears that Level I robots could theoretically replace about 1.5 million metalworking craft workers, semiskilled machine operators, and laborers, and Level II robots could theoretically replace about 4 million of the current 10.4 million of these workers. However, the time frame for this displacement is at least 20 years. In the coming decades the capabilities of robots can be expected to increase further, and their potential for displacing operatives will increase. On the other hand, not all of the potential displacement will actually be realized, and if the economy grows as anticipated, some of the jobs lost due to displacement of people by robots could be offset by increases in other manufacturing employment.

By around 2010 it is conceivable that more sophisticated—Level III?—robots will replace almost all operative jobs in manufacturing, about 9 percent of today's work force, as well as a number of skilled manufacturing jobs and routine nonmanufacturing jobs. Concerted efforts should be made by the private and public sector to prepare the future work force to respond to these changes. Even though several million jobs in the current manufacturing work force are vulnerable to robotization, the transition seems hardly catastrophic on a national scale, provided that new job entrants are properly trained and directed. In our view the oncoming transition will probably be less dramatic than the impact of office automation over the same period. By 2010 most current operatives would have retired or left their jobs. The jobs would not disappear all at once, and robot manufacturing programming and maintenance will provide some new jobs, although we think most new jobs will not be in manufacturing, despite the rapid growth of the robotics industry. New growth sectors in the economy, including undersea and space exploration, may also provide many new jobs. The important conclusion is that young people seeking jobs in the near future will have to learn marketable skills other than welding, machining, and other operative tasks that are now being robotized.

Even though the adjustment problems seem manageable, the potential for social unrest in specific locations cannot be dismissed so lightly. Consider the following points:

1. Nearly half of all the unskilled and semiskilled operative workers—the types of jobs that could be replaced by robots—are concentrated in four metalworking industries (SICs 34-37). Almost one-half of all production workers in these four industries are geographically concentrated in the five Great Lakes states—Indiana, Illinois, Michigan, Ohio, and Wisconsin—plus New York and California. In these first five states the metalworking sector also accounts for a large percentage of the total statewide employment in manufacturing. Adjustments in response to the rapid diffusion of robotics may be intensified in these areas. The adverse effect of not improving the productivity and competitive standing of these industries would also be concentrated in the same few states, of course.

2. Older established workers will generally be protected by union seniority rules, except in cases in which the whole plant closes. Unfortunately this is happening with increasing frequency. Even in the newest, most efficient plants, some younger workers with less seniority may be bumped. In either case the displaced worker starts again at the bottom of the ladder. Thus reemployed displacees are also more vulnerable to subsequent layoffs. A class of perpetually insecure, marginal workers could result. This would be a potential source of social problems and political dissension.

3. The states where jobs are most likely to be lost to robots are mainly in the north central region, where industry is also most unionized, plants are oldest, and wages are highest. The Sunbelt states, where many new jobs are being created, have new plants and lower wages. Many displacees will have to migrate to other regions. Those unable to upgrade their skills sufficiently might have to accept lower-paying service jobs or join the underclass of insecure marginal workers who never became established with a stable employer.

4. There would likely be a disproportionate effect on racial minorities and women. Nonwhites account for only 22 percent of the national work force but over 16 percent of total employment in semiskilled and unskilled manufacturing jobs. Women employed in semiskilled and unskilled manufacturing jobs are less likely to be represented by labor organizations than their male counterparts. De facto economic discrimination will accordingly increase.

5. Unions representing the affected categories of workers will probably ex-

perience sharp declines in membership and political and economic clout. A policy of organized resistance to the introduction of labor-saving technologies might seem attractive to fearful workers and their unions, resulting in a severe drag on the productivity of the manufacturing sector.

### JOB OPENINGS

In the occupations expected to be primarily affected by robotization, the job openings likely to be created by attrition in the 1980s provide a basis for assessing policies dealing with displacement during the next two decades. Attrition rates for semiskilled workers in metalworking are approximately 3 percent per year, depending on the sex and age distribution of the persons employed. However, these figures substantially underestimate the number of people transferring out of specific occupations, since they only include people who leave the establishment.[17] A 3 percent annual attrition rate suggests an annual average of about 170,000 job openings among blue-collar workers in the metalworking industries alone during the 1980s.[18] If one-half of these openings could be filled by operatives displaced from other jobs by robots, an average of over 85,000 jobs a year, or nearly 850,000 during the decade, could be filled while still accommodating some first-time job seekers.

As the number of new entrants into the labor force declines in the 1980s because of the drop in birth rates after the mid-1960s, older and more experienced blue-collar job seekers will face less competition from younger workers than in the 1970s. However, an unresolved question at this point is the extent to which economic growth or continued recession in basic industries such as automobile and steel will increase the number of job seekers competing with employees displaced by robotization. In a declining industry, moreover, openings that would otherwise be created by attrition are often left unfilled. Turnover openings that would arise from occupational mobility can fall off sharply as fewer persons are added to the employment roll and few quit voluntarily to take any other positions.

Many of the blue-collar workers displaced by robots would have the educational qualifications for more skilled training, which would lead to a better-paid position in other occupations. The traditional stereotype of a factory operative has been that of a person with limited education, often a functional illiterate. For a generation the typical educational level for operatives was in fact below that of the overall work force. In the mid-1950s, for instance, the median number of years of schooling completed by operatives was 9.5, compared with 11.7 years for all employed civilian workers. By 1978, however, the median for operatives, excluding transport operatives, was 12.1 years, compared with an overall work force average of 12.6 years. Operatives as a group tend to have at least a high school education or its equivalent. This can provide a basis

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[17] Attrition is used to refer to workers who leave the establishment as a result of quits, discharges, permanent disability, death, retirement, or transfers to other companies. The other main source of labor turnover is layoffs, suspensions without pay for more than seven consecutive days, initiated by the employer. Together the attrition and layoff rates comprise the total separation rate.

[18] Assume 6.7 million blue-collar workers in metalworking jobs, and an average rate of 3 percent decrease per year over a 10-year period.

for further specific vocational training or for further higher education in a two- or four-year college.

Changes in national priorities could also expand the range of job openings and thus make obsolete projections such as those of the Bureau of Labor Statistics, which are based on the experience of the recent past. A shift in national priorities favoring more adequate home care, income support, and medical services for the elderly, the retarded, and the handicapped would be reflected in new kind of jobs for persons with the appropriate training. Private and public efforts to rehabilitate physical infrastructure—bridges, subways, water and sewer systems—could create a large number of job openings that could partially be filled by displaced production workers.

The 40-hour standard work week has remained unchanged in most manufacturing industries for the past 20 years. White-collar workers typically enjoy a shorter work week. For example, two-thirds of all office workers in the finance, insurance, and real estate sectors now work less than 40 hours per week. A gradual reduction in the standard work week, leaving hourly wages unchanged, would diminish job losses by spreading the available work over more employees. Clearly the reduction in annual work hours could be accomplished in various ways. Sabbaticals, now confined to teachers and to some civil servants and steelworkers, could be extended generally to production workers. Required sabbaticals at part-pay could be used to explore another occupation, to care for babies, or to become a student again. Blue-collar workers returning to or first entering a university while on sabbatical could provide a new market for the services of colleges and universities faced with shrinking enrollments because of low birth rates two decades earlier.

explore another occupation, to care for babies, or to become a student again. Blue-collar workers returning to or first entering a university while on sabbatical could provide a new market for the services of colleges and universities faced with shrinking enrollments because of low birth rates two decades earlier.

## CONCLUSION

Despite the present limitations on robot capabilities and the incremental penetration of robotics into the economy, over the next two decades it would be wrong to assume that this phenomenon is just a continuation of mechanization and automation. That would be only partly true, for two reasons.

First, as extensions of human physical abilities, earlier machines took over many physical tasks, but in no sense did they exclude humans from the production process. Humans have always been needed to operate the machine. What is new is that sensate robots are now becoming capable of replacing humans. Thus robots are now or soon will be competing directly with humans for certain routine jobs involving relatively low levels of visual or tactile ability and relatively little intelligence—that is, problem-solving ability. The implications for future employment opportunities and education and training needs are profound.

Second, while robots are having their biggest immediate economic effect in the manufacturing sector, their greatest long-term effect is very likely to be in other areas. Four examples of future applications come immediately to mind: (1) household robot servants; (2) robot assistants for the physically handicapped, including leg amputees, paraplegics, quadriplegics, and so on; (3) robot soldiers; and (4) robot workers for deep underground mines, underwater activities, and industrialization of outer space. By the middle of the twenty-first century historians looking back may see much greater significance in one or more of these advanced applications than in the more pedestrian ones we have discussed at length in this article. Nevertheless the first steps must be taken successfully before any subsequent developments can occur. For the rest of the twentieth century the place of robots will be mostly in the factory.