Impacts of Robotic and Flexible Manufacturing Technologies on Manufacturing Costs and Employment

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Abstract

The issues analyzed in this paper are the extent to which unit costs and production labor requirements might be reduced in manufacturing industries if there were more widespread use of industrial robots and flexible manufacturing systems. These issues are analyzed from two perspectives. The technological focus of the first perspective is confined to the use of robotic manipulators. The percent of the production worker jobs that could be replaced by robots is estimated. Reductions in unit cost are calculated by assuming that a given percentage of labor costs is reduced. The technological focus of the second perspective is the integration of robots with other types of computer assisted manufacturing (CAM) technologies into flexible manufacturing systems. Potential increase in output that could be realized in low-, medium-, and high-volume plants, if machines were fully utilized, is estimated. Based on an analysis of a large cross section of metalworking industries, a relationship is specified between the level of output and the level of unit cost. Using these results, potential reductions in unit cost for low-, medium-, and high-volume plants are estimated.

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1. Overview

The issues analyzed in this paper are the extent to which unit costs and production labor requirements might be reduced in manufacturing industries if there were more widespread use of industrial robots and flexible manufacturing systems. The analysis is reported in detail in [Miller 83]. These issues are analyzed from two different perspectives. The technological focus of the first perspective is narrowly confined to the use of robotic manipulators. It is assumed that robotic manipulators will be "retrofitted" into existing production facilities without making major changes in the organization of production within the factory, other than modifying individual work stations so that robots can replace one (or perhaps several) operators. The critical variable in this perspective is an estimate of the percent of the production worker jobs that will be replaced by robots. Reductions in unit cost are calculated by assuming that a given percentage of labor costs is reduced. Cases are also considered where robot use results in a moderate increase in output as well as a decrease in production labor requirements. The question of whether decreases in production labor requirements could be offset by a increase in demand stimulated by a reduction in price is also analyzed.

The technological focus of the second perspective is much broader than the first, and is concerned with the impacts of integrating robots with other types of computer assisted manufacturing (CAM) technologies into flexible manufacturing systems. It is assumed that a factory using general purpose machines to produce specialized products in batches can be reorganized and integrated so that machines are fully utilized and used more efficiently. One critical variable in this perspective is an estimate of the potential increase in output that could be realized if all of the time in a year available for production were utilized. The other critical variable is an estimate of the unit cost and of the labor requirements in a fully utilized batch production plant. Based on an analysis of a large cross section of metalworking industries, a relationship is specified between the level of output and the level of unit cost. Reductions in unit cost for a given increase in output are derived from this relationship. Reductions in unit labor requirements are calculated in a similar manner.

2. Metalworking Industries

To date, 80 to 90 percent of the robots used in the United States and in Japan, as well as in the rest of the world, have been installed within a subset of manufacturing industries referred to as the metalworking sector. For this reason, the analysis of the potential impacts of robot use on unit cost and on production labor requirements focuses on the industries included in the metalworking sector.

What is a *metalworking* industry? This simply means that all or most of the establishments classified within the industry are involved to some degree in the shaping, finishing, and assembling of metal products.[1] Which industries are metalworking industries ? One way to answer this question is to identify those industries which use the "metalworking equipment" - metal cutting machines, metal forming machines, joining equipment, and other types of inspecting, and finishing equipment. Every five years since 1925, the American Machinist Magazine has conducted a census of metal shaping, metal forming and related metalworking equipment. Industries within the following major SIC groups were included in the American Machinist Inventory conducted between 1976-1978:

SIC CODE	Major Group Name
25	Furniture and fixtures
33	Primary metals
34	Fabricated metal products
35	Machinery, except electrical machinery
36	Electrical equipment and machinery
37	Transportation Equipment
38	Precision Instruments
39	Miscellaneous Manufacturing

Only the industries in major groups SIC 34-37 are included in most of the subsequent analysis. These four "core" groups include over 85 percent of the units of metalworking machinery counted in the American Machinist Inventory, and nearly 85 percent of the total employment. One major group, SIC 33, primary metals, can be distinguished from the other major groups because the major activity of most of its industries is the conversion of unprocessed metal ores into standard shapes (bar stock, sheets, tubes, pipes, plates, etc.). By contrast, the primary activity of all of the industries in major groups SIC 34-37 includes either the fabrication, finishing or assembly of products from standard metal shapes, and from other purchased parts and subassemblies. Industries in major SIC 33 are omitted from most of the subsequent discussion since the metal refining process is very different from the processes of fabrication, finishing and assembling. Only some of the industries in major groups SIC 25, 38 and 39 are classified as being in metalworking. Since these industries account for a relatively small percentage of the machines used and of the people employed, they too are excluded from the definition of metalworking used here.

In 1980, almost 40 percent of the 20 million people employed in manufacturing and almost 40 percent of the value added in manufacturing were concentrated in the the four major groups of metalworking industries, SIC 34-37. About 50 percent of manufacturing employment and of value added are concentrated in SIC 33-38.

Vietorisz (1969) has described the metalworking sector as "the bellwether of economic growth" for an industrial society because all of the tools and capital equipment used by all manufacturing industries (including itself), and by all other sectors of the economy are produced within it. It is the place within the industrial system where new knowledge is embodied into a physical form, enabling it to be utilized throughout the entire economic system. Since all new products and processes require these capital goods, it is not farfetched to claim that much of the knowledge that becomes part of the economic system enters through the metalworking sector. To the extent that one believes that capital goods, and the role they play in the creating of new products and processes, are essential to economic survival and growth, one can argue that the importance of this sector goes beyond the number of people directly employed within it.

3. The Impacts of Robotic Manipulators

Surveys of the percentage of workers within selected occupations that could be replaced by robots have been collected from 22 manufacturing establishments where robots were either being used or where being seriously considered for use (Table 1). These survey estimates are used to estimate the percent of production workers in metalworking industries that could be replaced by Level I (insensate) and by Level II (sensor-based) robots.[2] The survey results are used as the basis for estimating the percent of jobs in all production worker occupations that could be performed by robots (Table 2).

It is estimated that about 10 percent of the jobs of manufacturing production workers could be performed by Level I (insensate) robots and about 30 percent by Level II (sensor-based) robots. The Bureau of Labor Statistics estimates there were 5.1 million production workers in

Table 1: Summary of Survey Responses of the Percent of Jobs That Could be Robotized by Occupation and by Level of Robot Technology

Job	Level	Number of responses	Min. response	Max. response	Aver., simple	Aver., weighted by distribution of employees	Aver., weighted by batch size distribution
ORDERED BY AVERAGE (SIMPLE) RESPONSE FOR LEVEL I							
Dip plater	I	6	20	100	48.3	55.7	43.7
	II	6	50	100	78.3	79.7	81.5
Punch press op.	I	5	10	100	45.0	44.3	39.0
	II	5	60	100	76.0	75.0	67.8
Painter	I	16	0	100	40.0	43.5	37.7
	II	15	0	100	62.3	66.8	60.5
Rivetor	I	3	5	100	38.3	40.5	25.2
	II	3	10	100	50.0	51.8	35.9
Shotblaster/ sandblaster	I	6	10	100	35.8	35.6	31.9
	II	6	10	100	35.8	35.6	31.9
Drill press op.	I	5	25	50	33.0	32.5	30.1
	II	5	60	75	67.0	67.0	64.8
Etcher-Engraver	I	5	0	100	27.0	29.9	24.3
	II	5	0	100	53.0	59.2	40.3
Welder	I	17	0	60	23.8	25.5	22.0
	II	17	10	90	45.6	45.7	47.8
Coil Winder	I	7	0	40	23.6	24.5	24.8
	II	7	15	50	38.6	40.2	39.7
Heat treater	I	3	5	50	21.7	22.7	16.8
	II	3	40	90	60.0	61.1	52.5
Machine tool-NC	I	20	0	90	19.8	21.7	18.4
	II	19	0	100	44.7	46.5	41.2
Grinding/abrading machine op	I	5	10	20	18.0	18.2	19.3
	II	5	30	100	58.0	57.5	53.5
Lathe/turning machine op.	I	5	10	20	18.0	18.2	19.3
	II	5	25	65	50.0	50.4	50.0

Table 1, Continued

Conveyor operator	I	14	0	50	17.5	14.9	18.7
	II	14	15	65	33.2	41.9	33.2
Electroplater	I	6	5	40	17.5	18.1	15.2
	II	5	15	60	43.0	42.9	44.5
Milling/planning machine op.	I	5	10	20	16.0	16.1	16.9
	II	5	40	60	52.0	52.1	50.7
Filer/grinder/buffer	I	13	0	35	12.1	9.8	11.6
	II	13	5	75	27.7	27.6	26.2
Packager	I	15	0	40	11.8	10.8	8.7
	II	15	0	70	27.1	26.5	23.5
Pourer	I	3	5	20	11.7	10.9	13.1
	II	3	10	30	20.0	21.4	20.0
Assembler	I	19	0	40	10.3	8.9	9.5
	It	19	15	60	31.1	28.8	29.4
Composites and bonded structures	I	1	10	10	10.0	10.0	10JO
	II	1	40	40	40.0	40.0	40.0
Sheet metal op.	I	1	10	10	10.0	10.0	10-0
	It	1	40	40	40.0	40.0	40J)
Inspector	1	19	0	25	8.2	7.5	7.9
	ti	19	5	60	29.2	30.4	28.3
Caster	I	4	5	15	7.5	ae	7.2
	n	3	10	20	ISJO	15.2	15.9
Electronic wirer	i	3	0	10	6.7	TM	7^
	11	3	10	50	mj®	27.6	32.0
Order filer	i	9	0	20	BJ	6.3	5^
	i	9	0	80	29,4	31.7	25.3
Test^	i	17	0	to	5,3	4^	5.1
	i	17	0	30	11-4	.11J3	ias
Mixer	i	3	0	m	5.0	6.0	5^
	i	3	10	w	WM	WM	10,0
Tender	i	2	0	m	m	&4	5.5
	it	2	20	20	20.0	20J0	mo
Mftwigf*	i	4	0	15	&7	44	10
	M	4	0	15	&7	44	ao

Table 1, Continued

Kiln-furnace op.	I	3	0	10	3.3	2.9	2.0
	II	3	5	20	13.3	14.7	10.5
Tool and die maker	I	8	0	5	1.5	1.3	0.9
	II	8	0	60	16.6	15.3	9.2
Oiler	I	3	0	0	0.0	0.0	0.0
	II	3	0	0	0.0	0.0	0.0
Rigger	I	2	0	0	0.0	0.0	0.0
	II	2	0	0	0.0	0.0	0.0
Trader/helper	I	1	0	0	0.0	0.0	0.0
	II	1	50	50	50.0	50.0	50.0

For each occupation, the simple average is given by:

$$a_{simple} = (1/n) * \sum_{i=1}^{n} p_i$$

with

n = total number of respondents for the specified occupation

p_i = the i^{th} respondent's estimate of the percent of of workers in the given occupation whose jobs could be performed by a robot (Level I or Level II).

For each occupation, the average weighted by size of establishment is given by:

$$a_{size} = \sum_{j=1}^{4} s_j * a_{simple, j}$$

with

j = index of size classes of respondents
j = 1, 1-99 production workers in the establishment
j = 2, 100-499 production workers
j = 3, 400-999 production workers
j = 4, > 1000 production workers

s_j = percent of metalworking production workers employed in establishments of given size class.

For example, s_1 = .216 = percent of metalworking production workers employed in establishments with 1 to 99 production workers.

$a_{simple, j}$ = simple average of substitution estimates of respondents who are in size class j.

Table 1, Continued

For each occupation, the average weighted by batch size distribution is given by

$$a_{batch} = \sum_{k=1}^{3} b_k * a_{simple,\,k}$$

with
k = index of batch sizes of respondents
k = 1, custom and small batch production
k = 2, large batch production
k = 3, mass production

b_k = percent of value added in the metalworking sector produced by industries predominated by batch size class j.
For example, b_1 = .554 = percent of value added in the metalworking industries produced by industries predominated by small batch production.

$a_{simple,\,k}$ = simple average of substitution estimates of respondents who are in batch size class k.

Table 2: Summary of Survey Estimates of Potential Displacement of Production Workers: All Occupations

Occupation	Percent Displacement Level I	 Level II
Tool handlers	27.2	46.7
Metalcutting Machine Operators	15.5	42.6
Metalforming Machine Operators	26.2	55.0
Other Machine Operators	13.2	26.2
Assemblers	8.9	28.8
Laborers	3.8	27.7
Miscellaneous Craft Workers	2.8	13.2
Maintenance and Transport Workers	0.0	0.0
Totals	10.6	28.6

The average percentage displacement within each group of occupations is based on an analysis of the occupational employment within one particular industry group, SIC 351. The percentages would vary somewhat if they were based on the occupational employment of all industries with SIC 34-37.

Table 3: Number of Jobs Displaced and Robot Population Implied by Ayres/Miller Estimates of Potential Displacement

NUMBER OF JOBS DISPLACED

Industries	Employment (1980)	Potential Displacment by	
		Level I	Level II
Metalworking (SIC 34-37)	5,091,800	539,731	1,456,255
All Manufacturing (SIC 20-39)	14,190,289	1,504,171	4,058,423

ROBOT POPULATION IN METALWORKING AND IN ALL MANUFACTURING

Industries	Number of robots assuming 1 robot replaces		
	2 Workers	3 Workers	4 Workers
<u>Metalworking, SIC 34-37</u>			
Level I .54 million workers displaced)	270,000	180,000	135,000
Level II (1.5 million workers displaced)	728,100	485,400	364,000
<u>All Manufacturing, SIC 20-39</u>			
Level I (1.5 million workers displaced)	750,000	500,000	375,000
Level II (4.0 million workers displaced)	2,000,000	1,333,333	1,000,000

SIC 34-37 in 1980. Based on the estimates of the percent of jobs that could be performed by robots and of the number of production workers, it is estimated that Level I robots could potentially perform the jobs of 540,000 workers in SIC 34-37 and that Level II robots, if available, could potentially perform the jobs of 1.45 million workers in these same industries (Table 3). Extrapolating the job displacement data within metalworking to the 14.2 million production workers in all of manufacturing, it appears that level I robots could theoretically replace about 1.5 million jobs and that level II robots could theoretically replace about 4 million jobs. Assuming 1 robot replaced two production workers, these estimates of the potential for robot use, based on an analysis of robot capabilities and job requirements, imply that there is a potential use for over 700,000 Level I robots or for over 2 million Level II robots throughout all manufacturing.

Most market forecasts place the cumulative robot population for 1990 within the range of 50,000 to 150,000 units (Table 4). Assuming each robot is used to displace two workers, on average, this implies that only 100,000 to 300,000 workers will be lost, displacing only 0.7 to 2 percent of manufacturing production workers. Considering only Level I robots, the estimate of the potential number of applications is 5 to 15 times larger than the market forecasts of the Level I robot population for the year 1990.

An attempt is made to explain this large difference between the estimate of the technical potential for robot use and the estimates of actual robot sales. The cost of installing robots for loading and unloading machine tools is analyzed for the purpose of identifying the conditions under which there would be a strong economic incentive to use robots given that there is a technical potential for doing so. The analysis considers the purchase price of the robot as well as the additional implementation costs that are typically required. The assumptions made in calculating total implementation cost, for low cost, medium cost and high cost robots, shown in Table 5, are based on the observations that

- the ratio of total implementation cost\robot base price ranges from a factor of 3 to 5 in retrofit situations,
- application costs are a larger multiple of the robot base price for lower cost robots then for the higher cost robots,

and on the estimates of 1982 robot base prices. The summaries of the total implementation cost for retrofitting low cost, medium cost and high cost Level I robot systems into a factory to load and unload machine tools is given in Table 6.

Table 4: Forecasts of the Population of Robots in the the U.S. in 1990

Source of Estimate	Cumulative Population
Hunt and Hunt (Upjohn Institute)	50-100,000
Conigliaro (Bache, Halsey and Shields)	122,000
Aron (Dawia Securities)	94-95,000
University of Michigan/ Society of Manufacturing Engineers Delphi Survey	150,000
Engelberger (Unimation, Inc.)	150,000
Robot Institute of America	75-100,000

Source: Hunt and Hunt (1982: 25).

Table 5: Assumptions For Calculating Total Implementation Costs

TYPE OF ROBOT	BASE PRICE	TOTAL IMPLEMENTATION COST / ROBOT BASE PRICE
lower cost	$20,000	4
medium cost	$60,000	3
high cost	$100,000	2

Table 6: Summary of Cost Assumptions for Retrofitting Level I Robot Systems

Robot Hardware Cost (R)	Development Cost (D)	Total Implementation Cost (I = R + D)	Operators Replaced Per Shift
20,000	80,000	100,000	1
60,000	180,000	240,000	1-2
100,000	200,000	300,000	1-3

Table 7: Simple Payback Periods For Level I Robots Based On Labor Savings

25 K PER WORKER PER YEAR

Scenario:	Number of shifts per day		
Replacement rate per shift	1 shift	2 shifts	3 shifts
1 robot: 1 worker			
25 K robot	4.0	2.0	1.3
60 K robot	9.6	4.8	3.2
100K robot	12.0	6.0	4.0
1 robot:2 workers			
60 K robot	4.8	2.4	1.6
100 K robot	6.0	3.0	1.9
1 robot: 3 workers			
100 K robot	4.0	2.0	1.3

30 K PER WORKER PER YEAR

Scenario:	Number of shifts per day		
Replacement rate per shift	1 shift	2 shifts	3 shifts
1 robot:1 worker			
25K robot	&3	1.7	1.1
60 K robot	ao	4.0	2.7
100 K robot	10.0	5.0	3 3
1 robot2 workers			
60 K robot	4.0	2.0	1.3
100 K robot	5.0	2.5	1.7
1 robot 3 workers			
100 K robot	3.3	1.7	1.1

3.1. Calculation of Payback Periods Based on Direct Labor Savings

A cost-benefit framework is adopted where the benefits are *narrowly* defined as labor savings, and where costs are the total costs of implementing the robot system. While other benefits are sometimes realized when robots are used, such as more consistent and higher quality processing, increased throughput, and improved conditions for workers moved out of unpleasant jobs, labor savings are widely regarded as the primary (and often the only) variable to consider. Engelberger (1980: 103) makes the point quite clearly:

> The prime issue in justifying a robot is labor displacement. Industrials are mildly interested in shielding workers from hazardous working conditions, but the key motivator is the saving of labor cost by supplanting a human worker by a robot. So very much the better if a single robot can operate for more than one shift and thereby multiply the labor saving potential.

The respondents to the CMU robotics survey [Carnegie-Mellon 81] and all other available evidence [Whitney et al: 81];[Industrial Robot 81]; [Ciborra, Migliarese, and Romano 80] strongly supports this view. Respondents to these survey overwhelmingly ranked efforts to reduced labor costs as their main motivation for installing robots. Payback periods are calculated under various assumptions regarding the total annual cost of a worker and the number of workers replaced per robot (Table 7). Based on comments in the literature on the economic justification of robots [Smith and Wilson 82], it is assumed that a robot would only be installed if the projected payback periods were three years or less.

The cost of installing one robot is considered. This also includes the case of multiple installations if the cost of installing *n* robots is *n* times the cost of installing one robot. If the three year payback period were really a hard and fast rule (which it is not, of course), one would conclude from this simplified analysis that given the technical feasibility of using Level I robots, the only users would be

- those plants with enough demand to operate on a three shift bases.
- those plants where it was possibly to eliminate two or more workers per shift on two shifts with one robot.
- and those plants which could use the low cost (low capability) robots to eliminate one worker per shift for two shifts.

Taking a conservative outlook, suppose it were the case that one robot only eliminated one worker per shift, that paybacks were calculated on a two shift basis, and that the "heavy duty" robots were required for most machine loading applications, especially in "heavy" manufacturing. Payback periods would range between 4 and 5 years, depending on total worker costs. These longer than desirable payback periods would probably discourage many financial analysts from giving the "go ahead" on robot application. The conclusion here is that if one takes the most conservative view of the the economics of robot use (e.g., robots are only viewed as labor savers and must pay for themselves in a very short time period), than it appears that too long of a payback period (or correspondingly, too low of a return on investment) will restrain the growth of robot use over the next several years. Given the assumptions of this cost-benefit model, the conclusion is that substantially fewer robots would be installed than could be used. This would mean that the number of jobs displaced would be closer to the levels implied by the current market forecasts than by the survey based estimates of the potential for robot use.

A key assumption in the first cost-benefit analysis is that the cost of installing *n* robots is *n* times the cost of installing one unit. According to applications engineers and consultants, this is not the case if additional installations are similar to one another. The development cost (planning, tooling, design of accessory hardware) for the second and subsequent applications are lower than for the first one. If one large establishment were to install many robots, or correspondingly, if one large firm were to install many robots across several plants, the average cost per robot would be less than if only one or several units were installed. In a second series of cost-benefit calculations carried out, the cost of installing *n* robots in an establishment (or across a company) is adjusted so that the development cost component of total costs decreases by 10 percent for each subsequent installation (Table 8).

Given this revised cost model, payback periods are calculated by size of establishment for one industry. Within establishments of a given size class, the number of workers displaced per establishment is derived from the total number of workers potentially displaced, the distribution of employment by size of establishment, and from the number of establishments within the size class. The result of this analysis is that payback periods are substantially shorter in the largest sized establishments (1000 and more production workers) than in the other size classes (Table 9). The reason being that the average cost per robot decreases as the number of robots installed increases, and it is assumed that more workers would be displaced in the establishments with more production workers.

An important conclusion of this analysis is that, given the cost assumptions, only the largest establishments could justify the use of robots under the conservative assumptions that one robot replaces a total of two workers, that "heavy duty", higher cost, robots are required, and

Table 8: Total and Average Cost For Multiple Installations of Similar Applications

Number of Robots	60 K ROBOT*		100 K ROBOT*	
	Total Cost (x 1000)	Avg. Cost per robot (x 1000)	Total Cost (x 1000)	Avg. Cost per robot (x 1000)
1	240	240	300	300
9	1642	182.5	2125	236.1
46	4429.6	96.3	6455	140.3

*) Base price

Total cost of installing n robots is approximated by

$$I_n = n * R + D* \sum_{0}^{n-1} (.9)^i$$

Assume: The development cost for each successive application decreases by 10 percent for similar applications.

I_n = total cost of installing n robots.
R = robot base price
D = development cost for first installation

Table 9: Payback Periods Based on Production Labor Savings by Size of Establishment

25 K PER WORKER PER YEAR

60 K ROBOT (Base Price)

Size of Establishment	1R:1W:2S	1R:1W:3S	1R:2W:2S	1R:2W:3S
1-19	9.6	9.6	9.6	9.6
20-99	4.8	4.8	4.8	4.8
99-249	4.5	3.1	3.1	1.6
250-499	4.4	3.1	2.4	1.7
500-999	3.1	2.4	2.0	1.5
1000 and >	1.9	1.5	1.3	1.0

100 K ROBOT (Base Price)

Size of Establishment	1R:1W:2S	1R:1W:3S	1R:2W:2S	1R:2W:3S
1-19	12.0	12.0	12.0	12.0
20-99	6.0	6.0	6.0	6.0
99-249	5.6	3.9	3.9	2.0
250-499	4.4	4.0	3.1	2.1
500-999	4.2	3.1	2.6	1.6
1000 and >	2.8	2.1	1.7	1.3

1R:1W:2S reads as follows:

One robot replaces one worker per shift for 2 shifts.

that labor savings are the only quantifiable economic benefit. Smaller size establishments, with only one or two applications, would not be able to realize the "scale economies" realized when multiple units are installed. Payback periods would be too high to obtain the financial approval for robot use.

Survey responses from 52 members of the Robot Institute of America indicate that as of 1981, robot use was heavily concentrated in establishments with 1000 and more production workers. The survey also showed that these large establishments typically used many robots. This lends support to the hypothesis that the economic incentives for robot use are much stronger in the largest sized establishments than in the smaller ones. It is also noted that the automobile industry, which has the largest proportion of production workers in large establishments, is also the largest user of robots. (The auto industry also has the highest wage rates of any industry in SIC 34-37).

Suppose it were assumed that robot use will continue to be heavily concentrated in the largest establishment and also in the metalworking industries (SIC 34-37) until the end of the decade. Almost 40 percent of the 5.1 million workers employed in these industries as of 1980 are located in establishments with 1000 or more production workers. To displace 10 percent of these workers would require almost 100,000 robots, assuming one robot displaces two people. Clearly, if some robots were used in smaller sized establishments, as well as outside of the metalworking industries, somewhat more than 100,000 robots would be required. (If robots were used to displace 10 percent of production workers in all manufacturing industries, it would imply a robot population of 180,000 units.) Most market forecasts predict their will be a total of 75,000 to 150,000 Level I robots in use throughout industry by the year 1990. It is plausible that these forecasts are predicated on the assumption that robots will mostly be used within the largest establishments in the metalworking industries, and that roughly 10 percent of the jobs in these establishments could be robotized.

This example shows that there is not necessarily an inconsistency between the estimate that 10 percent of production worker jobs could potentially be performed by Level I robots (implying a potential market of 750,000 robots) and that there are only expected to be 50,000 to 150,000 Level I robots in use throughout industry by 1990. It appears that the key to explaining the difference between the survey based estimates of technical potential for robot use and the market forecasts of the number of robots actually sold is an understanding of how large a segment of the potential market will have a strong enough economic incentive to install robots given that there is a technical potential for doing so.

Will robot use continue to be heavily concentrated in large establishments in metalworking as it has been, and as many market forecasters apparently expect that it will be ? It is important to know whether future robot use will follow the same market patterns as past use to understand the extent of potential labor impacts-- whether 10 percent of a small segment of the workforce will be displace or whether 10 percent of the total manufacturing workforce will be displaced. An understanding of the likely patterns of robot diffusion over the next several years would also help to understand whether or not initiatives might be required to promote robot uses in places where it might otherwise be indefinitely deferred, such as in smaller size establishments.

Is the use of Level II (sensor-based) robot systems going to alter the extent of robot diffusion and make it necessary to reevaluate the potential impacts on job displacement ? At this point, the answer appears to be no. Currently, sensor based systems with enough capability to acquire randomly oriented parts are substantially more expensive than Level I systems so the payback periods are much longer. Sometime within the next several years, the cost of sensor-based systems will drop substantially, and the answer may be yes.[3] Suppose, as a result of future technological improvements, that the cost of installing a Level II system was the same as the cost of installing a Level I system. There are perhaps three times as many applications for Level II systems as for Level I systems. There would be more potential applications per establishment, and even the medium size and smaller establishments would have use for several (or more) robots. Then installing three times as many robots means that the average cost per installation would be less than for Level I robots, assuming, as before, that the total cost of installing a robot decreases as the number of robots installed increases. Payback periods would decrease, especially for the medium and smaller size establishments. If this were to happen, there would be good reasons for reconsidering the market forecasts that predict that their will be *at most* 150,000 robots by the end of 1990. Given the plausibility of this scenario, future studies of robotic impacts should consider the rate at which the cost and capabilities of Level II robot systems are changing.

3.2. The Price Elasticity Argument

An analysis has been made of what would happen to production worker employment in an industry if robots were used to replace workers and if a decrease in price resulting from higher levels of productivity stimulated demand for the industry's output. The question of interest is whether or not price induced increases in demand could be expected to increase total labor requirements by a sufficient amount to offset job displacement in an industry using robots. In the first scenario, it is assumed that robots decrease cost only as a result of reducing labor requirements and that throughput is held constant. In the second scenario, it is assumed that robot use results in a 20 percent increase in throughput as well as a reduction in total labor requirements. In this scenario, unit labor requirements and production costs decrease by substantially more than in the case where throughput is held constant.

Given assumptions on the decrease in production labor requirements, and on the increase in the throughput of the factory, the amount by which the demand for output would have to increase in order to reabsorb all workers whose jobs are displaced is calculated. It is assumed that the demand for output increases as its price decreases. For every Δp percent decrease in price, demand for output is assumed to increase by ν percent, where the parameter ν is referred to as the price elasticity of demand. Given the calculated price change, the magnitude of the price elasticity of demand which would be required to induce enough of an increase in output so that employment levels would be maintained is calculated. The magnitude of this "break even" price elasticity is of particular interest. Clearly, if the magnitude of the price elasticity of demand were large enough, and if there were no limitations on how large the demand for output could increase, any decrease in labor requirements could be offset by price induced increases in the demand for output. The concern relevant to public policy is whether the calculated values for the price elasticities of demand required to maintain employment levels are near the levels of price elasticities normally observed in the "real world" marketplace.

For both scenarios, the increase in demand required to reabsorb all displaced workers and the value of the "break even" price elasticity is calculated with and without assuming that there are job turnovers as a result of attrition. In the case with "attrition," it is assumed that 15 percent of the workers in the industry leave the workforce as a result of death, retirement, sickness, disability, etc. during the period in which workers are replaced by robots. When attrition is considered, a smaller increase in demand and a smaller magnitude of the breakeven price elasticity is required to reabsorb workers displaced by robots since there are job openings created by job turnover.

The conclusion on whether or not jobs displaced by robots could be reabsorbed within the same industry is not conveniently summarized since it depends on several variables, including

1. the percent of jobs that are displaced,

2. whether or not robot use increases throughput as well as decrease labor requirements,
3. whether or not the there is job turnover due to attrition.

First consider the case of no attrition in the workforce to focus on whether price induced increases in demand, by itself, could be expected to offset job displacement. If throughput is held constant and price decreases are due only to decreasing a fraction of production labor cost (Scenario I, no attrition), it is concluded that very few of the displaced workers would be reabsorbed. If throughput were also to increase, thereby causing a larger decrease in price (Scenario 2, no attrition), it seems that a 10 percent displacement of jobs could be offset by price induced increases in output. However, demand would have to be relatively price elastic. Without considering attrition, the conclusion as to whether or not the potential job displacement of Level I robots could be offset depends on the extent of the economic benefits of robot use. Price induced increases in output would not fully offset the potential job displacement of Level II robots.

Now consider the case where the size of the workforce decreases by 15 percent as a result of attrition over a 3 to 5year period. If throughput is held constant (Scenario 1, attrition), and if 10 percent or fewer workers were displaced, job openings from turnovers would outnumber jobs displaced by robots, even without considering the effects of price decreases. If the use of robots were to also increase throughput (Scenario 2, attrition), it appears that a potential displacement of up to 20 percent could conceivably be offset through the combined effects of job turnover and price induced increases in output. Even with attrition, though, it is unlikely that a potential displacement of 30 percent could be offset. The conclusion here is that Level I robots could be fully utilized in an industry and displace 10 percent of the workers over a several year period without resulting in any unemployment. However, there would still be a significant numbers of jobs lost if Level II robots were fully utilized and 30 percent of the workers were displaced.

This analysis suggests that a more thorough and precise understanding is required of how robotics will alter labor requirements in order to further analyze employment issues in industries using robots. It is important to know if the economic benefits of robot use are restricted to savings in labor cost, or whether they might also increase throughput. It is also very important to know about the rate of job turnover, since the attrition is often cited as the way of offsetting displacement effects of robots. More detailed information on rates of attrition are needed to confirm the conclusion made here that up to 10 percent job displacement could be fully offset by attrition if there is no increase in throughput. This analysis also suggest there is a need to take a more detailed look at the rate of development of sensor-based robot systems.

Some of the assumptions underlying these conclusions need to be clarified in order to make the limitations of this analysis more transparent to the reader. First, issues relating to changes in skill requirements for a given occupation or changes in the overall occupation profile are not considered here. In this simplified framework, it is assumed that if a production worker is displaced by a robot and if there is a need for an additional production worker either as a result of an increase in demand or job turnover, then the displaced worker can be reabsorbed by the firm. Thus, it is assumed that the skills required by production workers after the implementation of robots do not pose a barrier to reabsorbing the displaced workers.

Second, all aspects of cost changes are not carefully considered. Increases in capital cost required to install robots is ignored in this analysis so the calculated price decreases can only be viewed as upper bounds. If capital cost were included and the decrease in price were smaller, then the magnitude of the price elasticity required to maintain employment levels would be larger. If the price elasticities were larger, it is possible that the percentage of job displacement that could be offset is smaller than indicated.

Third, only one industry is considered here and interindustry transactions are ignored. An important characteristic of most metalworking industries is that they sell most of their output to other industries (especially to other metalworking industries) to be used as capital or material inputs. Suppose all industries were to reduce their cost by a given amount, say 2 percent, in one period as a result of reducing labor cost, and bought and sold materials and equipment from one another. In the next period, all purchased materials and capital equipment would be 2 percent cheaper, so each industry would realize an additional one to two percent cost reduction. If these interaction affects result in larger price decreases than are are considered here, then the "breakeven" value of the price elasticity required to maintain employment levels would be smaller than is indicated. If the price elasticity were smaller, then it is possible that a larger percentage job displacement could be offset as a result of price induced increases in demand.

Fourth, relationships between the cost of manufactured goods and the level of economic activity in other sectors of the economy which use these goods are not considered. The possibility that employment losses in manufacturing might be offset by employment gains in other sectors of the economy which expand as a result of decreases in the cost of capital and consumer goods is not explored. More definitive conclusions require that these four factors be considered.

4. The Impacts of the Fully Utilized, Flexibly Automated Factory for Batch Production

The relationship between the level of unit cost and the level of output produced is examined across 101 different metalworking industries. An estimate of the pounds of basic metals and of processed metal inputs purchased is used as a surrogate measure of the level of output of each industry.[4] Value added per unit and units of output are computed for each industry using pounds of metal processed as the standardized unit of output (Figure 1).[5] Regression relations between unit cost and unit cost components are summarized in Table 10. The basic structural relationships that underlie the shape of a "neoclassical" long run unit cost curve for a particular product are also apparent in the comparison of unit cost versus output *across* industries. These basic relationships are:

1. Capital costs for equipment and machinery per unit of output decrease across industries as the units of output produced increases.
2. Production labor costs per unit of output decrease across industries as the units of output produced increases.
3. Value added per unit of output decreases across industries as the units of output produced increases.
4. Machine utilization increases across industries as units of output produced increases.[6]

The implication is that the tradeoffs which most strongly affect the organization of production within a particular plant--either organizing to make small volumes of specialized products at a high cost or organizing to make large volumes of standardized products at a low cost-- are also affecting the organization of production across industries.

Because it appears that the *custom-batch-mass* paradigm characterizes the organization of production across industries (as well as within specific plants), it is argued that that the dominant mode of technology used within an industry can be inferred from the industry's measures of pounds of metal processed and unit cost. Industries with the highest levels of production cost per pound of output and with the fewest pounds of output are classified as

Figure 1: Value AddedPer Pound of Metal Vs Pounds of Metal/Establishment for Metalworking Industries, 1977

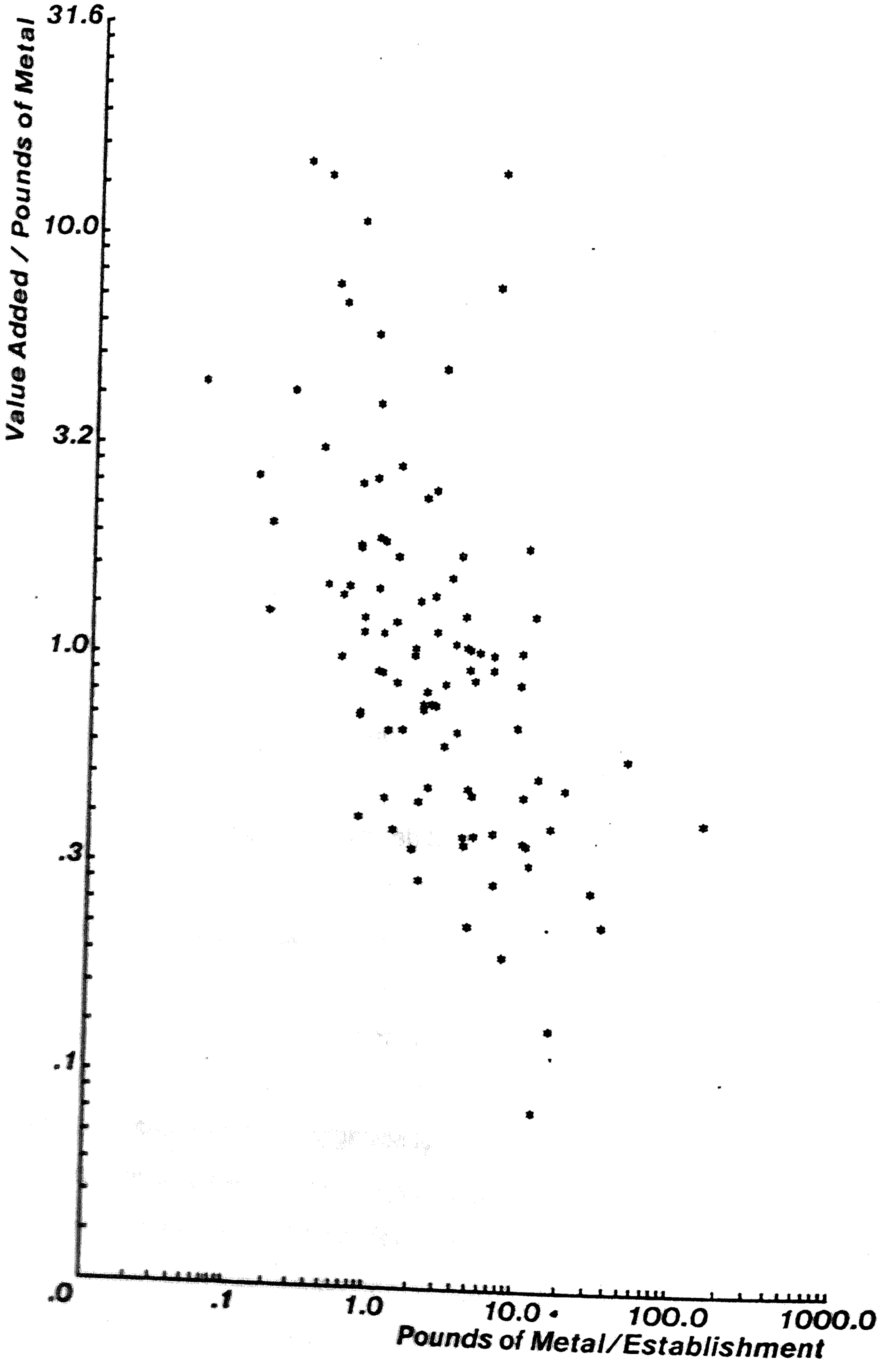

Table 10: Summary of Regression Results of Unit Cost Versus Pounds of Output/Number of Establishments Across Metalworking Industries

Dependent Variable	Constant b_0	Output elasticity b_1	Significance level for output elasticity	Goodness-of fit measure: R^2 (percent)
Pooled four digit data set, SIC 34-37: 101 four digit industries output = pounds of metal/number of establishments				
k/m	-0.7243	-0.371	0.99	22.5
	(-6.75)	(-5.49)		
l/m	-0.835	-0.440	0.99	35.5
	(-8.95)	(-7.49)		
va/m	0.401	-0.436	0.99	31.4
	(3.96)	(-6.83)		
k/l	-0.056	0.051	0.95	3.1
	(-1.41)	(2.06)		
k/employee	2.160	0.156	0.99	19.9
	(44.17)	(5.08)		
s/l	-0.473	-0.114	0.99	10.5
	(-9.34)	(-3.57)		

( ) = t ratio for estimate.

Unit Cost Components (Dependent Variables)

k/m = gross value of equipment and machinery / pounds of metal
l/m = all included production worker costs / pounds of metal processed
va / m = value added / pounds of metal
k/l = gross value of equipment and machinery / all included production worker costs.
k/e = gross value of equipment and machinery /total employees
s/l = salaries / hourly production worker wages

Output Measure (Independent Variable)

m/e = pounds of metal processed/number of establishments

Output elasticity for each cost component is the estimate of b_1 in
$E[\ln(\text{unit cost component})] = b_0 + b_1 \ln(m/e)$

Table 11: Distribution of Value Added by Mode of Production, SIC 34-37

Region and Mode of Production	Major SIC Groups 34	35	36	37	Total, 34-37
	PERCENT OF VALUE ADDED FOR INDUSTRIES IN SAMPLE				
Custom and Small Batch	1.1	41.0	58.5	30.6	31.5
Mid-Batch	28.3	42.5	30.2	6.9	26.4
Large Batch	45.5	16.5	3.1	2.9	16.4
Mass	25.1	0.0	8.2	59.6	25.7
Sample coverage of value added in all industries	94.2	95.8	51.2	97.4	86.0

Table 12: Distribution of Output by Mode of Production, SIC 34-37

	PERCENT OF TOTAL OUTPUT FOR INDUSTRIES IN SAMPLE				
Custom and Small Batch	1.0	36.3	55.1	20.1	24.8
Mid-Batch	25.3	44.3	31.4	4.9	23.3
Large Batch	45.1	19.4	3.8	2.8	19.9
Mass	28.6	0.0	9.7	72.2	35.7
Sample coverage of output in all industries	95.1	96.1	51.0	98.0	88.0

being comprised of custom and small batch producers. Industries with the lowest levels of production cost per pound of output and with the most pounds of output are classified as being comprised of mass producers. The remaining industries, those with mid range levels of production cost per pound of output and with mid range levels of pounds of output, are classified as being comprised of batch producers. With these assumptions, the proportion of value added and of output accounted for by metalworking products which are custom, batch and mass produced is estimated. The result of this analysis is that the industries with the highest levels of output and with the lowest levels of unit cost (which are assumed to be the mass producers) account for *at most* 25 percent of the value added and for less than 35 percent of the total output of the 101 industries in the sample[7] (Tables 11 and 12). This analysis corroborates the widely cited claim that most of the value added in the metalworking sector is accounted for by products which are batch produced.

The significance of the claim that most industries in metalworking produce batches of specialized products can only be appreciated by considering the difference in unit cost between batch and mass production. One finding is that a previously published estimate claiming by Cook (1975) that for the case of a typically machined product, the unit cost using the most efficient mass production techniques would be 100-500 times lower than if the produced were produced in a "one-of-a-kind" mode, and 10-30 times lower than if it were batch produced seems reasonable. Considering that 1) most of the value added in metalworking is accounted for by batch production, and 2) products which are batch produced are much more expensive than products mass produced in large volumes, it is typically argued that much of the value added within the metalworking sector can be viewed as a type of penalty cost that has been unavoidable because of the inherent inefficiencies of custom and batch production relative to mass production. This is the foundation for many of the arguments citing the need to accelerate the development and use of "robotic" and other types of flexible production technologies which are applicable to batch production.

An analysis is made of the decrease in unit cost and in labor requirements that would result if the use of robots, in conjunction with other types of automation, made it possible to substantially increase the capacity of a factory which uses general purpose types of machines to produce specialized products in batches. Previously published estimates of machine utilization in conventionally organized factories producing low and mid-volumes of specialized products [Mayer and Lee 80] are used to estimate the potential for increasing output. The conclusion is that output in batch production facilities could theoretically be increased by 150 to 550 percent if all of the productive time available in a year were fully utilized and if the plant were organized to work more efficiently (Table 13).

Published information on flexible manufacturing systems indicate that with the most advanced types of flexible automation currently available, parts of the manufacturing process can be *fully* automated even when making specialized products in batches . In these systems, the output is several times that of its conventional counterpart, which is consistent with the range of increase derived from the analysis of theoretical capacity. Robotic manipulators, per say, are only a very small part of the total automation used in these plants. This suggests that when analyzing the case of a fully utilized plant running around the clock, one should more appropriately address the potential impacts of flexible automation *systems* on cost and employment, as opposed to the impacts of robotic manipulators. Also, these examples indicate that very large capital investments are required to design and install such systems.

To date, it has not been possible to make a detailed comparison of the capabilities and economics of flexibly automated plants against those of conventionally organized ones because the published information on the handful of flexibly automated plants throughout the world is too sparse. Given that the unit cost in the proposed high volume batch production plant can not be directly observed, it must be inferred or approximated through some indirect means. The framework used here for estimating the potential reduction in unit cost is to assume that a flexibly automated plant producing specialized products in small and medium sized batches would have some of the characteristics of conventional plants producing more standardized products in larger volumes. Thus, the unit cost observed in industries dominated by plants using conventional (e.g., specialized) types of automation to make more standardized types of products in larger volumes is used to infer the level of unit cost in a fully utilized flexibly automated batch production.

A regression relationship between unit cost and units of output produced across

Table 13: Summary of Potential Increases In Output.

Type of Plant		Potential Capacity Increases	
	Base Case	Robots Only	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 (%)		**45**	82
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 (%)		152	230
Mid-volume			
Available hour index	1.00	2.98	2.98
Throughput index	1.00	**1.14**	1.55
Output index	1.00	**&40**	**4.62**
Increase in output {%)		**240**	**362**
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 (%)		**405**	**561**

Available hour index: The relative amount by which the time available for production could be increased. This includes the effects of recouping the days per year that the plant is not scheduled for production, as well as recouping the shifts per day that that are idle during those days that the plant is scheduled for production. One hour per day is allotted for preventive maintenance.

Throughput Index: The relative amount by which the time available for production could be increased during those times that the plant is operating. This includes the effects of reducing **set-up** time, loading/unloading time, tool change time, and idle time.

metalworking industries, estimated in Table 10, is used as a starting point for this analysis. The elasticity of unit cost with respect to output is used to derive the percent reduction in unit cost that would result from increasing output. Similarly, the elasticity of production labor cost with respect to output is used to derive the percent reduction in production labor requirements that would be realized with an increase in output.

A more detailed analysis of the variation in unit cost across industries is also carried out. The explanatory variables used in the expanded multiple regression model are summarized in Table 14. The proposed effect on unit cost is also shown by indicating whether the sign of the estimated elasticity of unit cost with respect to each variable should be positive or negative. A key feature of the more detailed analysis is that two surrogate measures of processing complexity are constructed which are believed to indicate important differences in the nature of the processing requirements across industries. One complexity measure is the average unit cost of the basic metals purchased by an industry, called the basic metal cost index (bmci). An increase in the index means that more expensive metals are used, which is taken as an indication that the difficulty of the shaping operations increases. Since more difficult operations require more capital and/or labor inputs to accomplish, unit cost is assumed to increase and the proposed sign of this elasticity is positive. The second complexity measure is the ratio of processed metal input cost to basic metal input cost. It is argued that this variable is an indicator of the relative proportions of assembly to metal shaping. It is included to account for the difference between industries which are primarily involved in shaping and forming versus those primarily involved in assembly. Two reasons for believing that a higher ratio of processed metal costs to basic metal costs indicates a more "complex" process are as follows. First, the higher the ratio of processed metal inputs to basic metal inputs, the greater the diversity of material inputs used in an industry. There is some tendency for the ratio of salary costs/production worker cost to increase across industries as the ratio of processed metal inputs/basic metal inputs grows larger. This provides some evidence that it takes more organizational control and supervision to coordinate production when there is a a larger proportion of processed metal inputs. Second, the inspection of assembled products requires more than just the verification of dimensions. Since subcomponents must be properly integrated with one another, testing is required to verify that final product performs its designated functions properly. With electronics equipment, and computers, this can be a fairly extensive and complicated processes. Also, several other variables which introduce noise into a cross sectional comparison, such as differences in wage rates and in the coverage of material inputs used to construct the output measure, are introduced into the multiple linear regression model.

Table 14: Summary of Explanatory Variables in Multiple Regression Model

FACTOR	VARIABLE	NOTATION	EFFECT ON UNIT COST (SIGN OF COEFFICIENT)
Level of output	$\frac{\text{pounds of metal processed}}{\text{number of establishments}}$	m\e	$\frac{d\ln(u)}{d\ln(m\backslash e)} < 0$
Complexity of metal shaping activities	$\frac{\text{dollars of basic metal}}{\text{pounds of basic metal}}$ = basic metal cost index	bmci	$\frac{d\ln(u)}{d\ln(\text{bmci})} > 0$
Degree of assembly	$\frac{\text{dollars of purchased metal}}{\text{dollars of basic metal}}$	pmbm	$\frac{d\ln(u)}{d\ln(\text{pmbm})} > 0$
"All included" hourly wage	$\frac{\text{production worker wages + benefits}}{\text{production worker hours}}$	w	$\frac{d\ln(u)}{d\ln(w)} > 0$
Material coverage	$\frac{\text{dollars of metals}}{\text{dollars of total materials}}$	c	$\frac{d\ln(u)}{d\ln(c)} < 0$

```
THE REGRESSION EQUATION IS
ln(u) = - 1.17 - 0.295 ln(m/e) + 0.983 ln(bmci) + 0.488 ln(pmbm)
 + 0.948 ln(w)   - 0.765 ln(c)
                                         ST. DEV.    T-RATIO =
VARIABLE            COEFFICIENT          OF COEF.     COEF/S.D.
Constant          -1.1707             0.4625         -2.53
ln(m/e)           -0.2947             0.0387         -7.61
ln(bmci)           0.9827             0.0909         10.81
ln(pmbm)           0.4881             0.0490          9.96
ln(w)              0.9806             0.1911          5.13
ln(c)             -0.7644             0.2051         -3.73

THE ST. DEV. OF Y ABOUT REGRESSION LINE IS
S = 0.3717
WITH ( 101- 7) =  95 DEGREES OF FREEDOM

R-SQUARED = 87.0 PERCENT
R-SQUARED = 86.3 PERCENT, ADJUSTED FOR D.F.
```

It is observed that industries with low levels of output tend to use more expensive basic metal inputs. This suggests that "scaling up" means more than just increasing the volume of production. There also tends to be a change in the mix of material inputs as well. It is believed that more standard material inputs are suggestive of simplified and standardized product designs. If this were the case, it would indicate that processing requirements themselves are simplified and standardized as the volume of output increases. For this reason, it is argued that the unit cost elasticity derived from the simple regression of unit cost against output without including the complexity parameters incorporates the effects of both increasing the average batch size and of standardizing the material inputs. When the basic metal cost index and the other explanatory variables are included in the regression analysis, the magnitude of the unit cost elasticity is lessened. The reason for this is that the effects of increasing the average batch size are separated from the effects of standardizing the material inputs when the complexity parameters (principally the basic metal cost index) are included in the multiple regression model.

If it were the case that each product is optimally designed for ease of manufacture in the flexibly automated batch production factory, as is typically the case with standardized products made in a conventional mass production factory, one would want the effects of both increasing batch size and of altering material inputs (and product design) to be included in the unit cost elasticity. If, however, each product were not designed to minimize the complexity of processing requirements, as is typically the case with making specialized products in a conventional batch production factory, then one would want to separate the effects of standardizing the material inputs from increasing the average batch size.

The unit cost elasticities estimated from the regression equations without and with the complexity parameters are shown in Table 15. The elasticities of total value added per unit of output are used to derive high and low estimates of the percent reduction in unit cost that would result from an increasing output from 50 to 1000 percent in a batch production plant (Table 16). The result is that severalfold increases in output would lead to a very substantial decrease in unit production cost. For example, if output were to increase by 100 percent, the estimated decrease in unit cost ranges from 18 to 26 percent. If output were to increase by 1000 percent, the estimated decrease in unit cost ranges from 50 to 65 percent.

It is emphasized that the analysis of the economics of the flexibly automated factory is more speculative than the analysis of the economics of robotic manipulators. Since the relationship

Table 15: The Elasticity of Unit Cost Components with Respect to Output

Unit Cost Component	Average Share of of Unit Cost^a (%)	Estimated Elasticity Unit Cost Component With Respect to Output:	
		With Complexity Variables^b	Without Complexity Variables^c
Total value added	100.0	-0.295	-0.436
1] Labor value added	55.9	-0.345	-0.461
1 a] Production worker costs	35.4	-0.306	-0.440
1 b] Salary costs	20.4	-0.406	-0.536
2] Nonlabor value added	44.1	-0.232	-0.408

value added = labor value added + nonlabor value added

labor value added = production worker costs + salary costs

a) Average share of total cost for 101 metalworking industries included in sample.

b) Output elasticity for each cost component is the estimate of b_1 in
$E[\ln(\text{unit cost component})] = b_0 + b_1 \ln(m/e) + b_2 \ln(bmci) + b_3 \ln(1 + pmbm) + b_4 \ln(w) + b_4 \ln(c)$

c) Output elasticity for each unit cost component is the estimate of b_1 in
$E[\ln(\text{unit cost component})] = b_0 + b_1 \ln(m/e)$

Table 16: Percent Decrease In Unit Cost Derived from Estimate of Output Elasticity

Percent Increase in Output	Percent Decrease in Unit Cost Assuming Elasticity Equals:	
	-0.295[a	-0.436[b
50	11.3	16.2
100	18.5	26.1
200	27.7	38.1
300	33.6	45.4
400	37.8	50.4
500	41.0	54.2
1000	50.7	64.8

a) Output elasticity derived from estimate of b_1 in

$$E[\ln(va/m)] = b_0 + b_1 \ln(m/e) + b_2 \ln(bmci) + b_3 \ln(1+pmbm) + b_4 \ln(w) + b_5 \ln(c)$$

b) Output elasticity derived from estimate of b_1 in

$$E[\ln(va/m)] = b_0 + b_1 \ln(m/e)$$

Δ unit cost $= (1 + \Delta \text{output})^{-b_1} - 1$

b_1 = elasticity of unit cost with respect to output between unit cost and the level of output is derived from an analysis of industries using the *current* generation of production technology, this is only an indirect analysis of unit production costs in a factory making use of the new generation of flexible production technologies. Hence, the analysis is, at best, suggestive of the economics of production in a newly designed, flexibly automated plant. It is not known whether a more direct and detailed analysis would yield the same conclusions. Nonetheless, if the inference of this analysis is correct, and it is the case that a flexibly automated batch production plant would have a substantial cost advantage over a conventionally organized facility, one would expect that these new types of plants would rapidly diffuse throughout manufacturing industries.

If unit cost in a fully utilized flexibly automated factory is so much less than in a conventional factory, one wonders why so few have been built. Is it too difficult and too expensive to build such a plant, or is it the result of other less tangible factors? No formal analysis has been carried out to address this question. However, a few informal interviews with major manufacturing companies revealed that several companies have plans on the drawing boards to build such plants. This suggests that within the next few years, more attempts will be made to construct flexible manufacturing systems in the U.S. Some executives commented that organizational barriers have stopped plans for building such plants. One interesting comment is that there are situations where such a plant would have more capacity than could be utilized by one division of a company. To be fully utilized, it would have to be shared across divisions. It has been suggested that this generates organizational resistance because the plant is no longer "captive" to one manager.

If a plant could be built that has several times the capacity of a conventional batch production plant, there is the possibility that several old plants could be closed down and their production consolidated into the new facility which has the flexibility to produce a mix of different products. This seems to be a likely scenario if the flexibly automated plant were built in a mature industry where the potential for market growth was limited. One example worked out, using the results presented here, shows that if three plants were closed down and their output consolidated into one high volume, flexibly automated plant, total labor requirements would decrease by 30 to 40 percent. This decrease in labor requirements is based on the elasticity of unit production labor cost estimated from the regression analysis (which is based on the use of conventional types of technologies across low, medium and high volume industries). The available information on the existing flexible manufacturing systems suggests that the one flexibly automated plant might have substantially fewer workers than even one of the smaller plants it replaces. If this were the case, the percentage decrease in total labor requirements would be much larger.

Since the flexible factory scenario holds the largest promise for reducing unit cost, and potentially poses the largest threat to employment in an industry, it warrants more serious analysis. Further research should focus on a more refined and direct analysis on the economics of production in flexibly automated factories, and on forecasts of their use throughout specific industries.

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[1] Throughout this paper, the Standard Industrial Classification System (SIC), use by the Bureau of the Census, is used to define industries and products.

[2] For one type of process, metalcutting machine tool operations, an estimate is made of the

percent of tools that could be operated by Level I and Level II robots in order to check the validity of the survey estimates. The two estimates of the potential for robot use in metalcutting machine operations, derived independently of one another, are in close agreement. It appears that the survey based estimates are good indicators of the potential for using robots to operate metalcutting machine tools, and there is no strong reason to disbelieve the survey based estimates of potential robot use in the other application areas either.

[3] In a state-of-the-art Level II application for machine loading developed at the CMU Robotics Institute, much of the added expense was the result engineering effort required to to improve the communication between the commercially available robot and vision system and the control of the overall system. The actual Level II hardware, the vision system, only accounted for a small part of the cost difference. It appears that if the vendors made minor modifications to their commercially available systems, it would be possible to achieve the degree of communication and control required for sophisticated applications without extensive engineering efforts. This would substantially reduce the cost of a Level II installation.

[4] The term "basic metals" refers to inputs of "raw" metal stock-- steel, brass and aluminum in the form of bars, billets, sheets, strips, plates, pipe, tubes, etc., as well as casting and forgings made of the three basic metals. The term "processed metals" refers to inputs which are themselves the products of the industries in major groups SIC 34-38. In general, these products are basic metals which have been further processed within the metalworking industry.

Pounds of metal processed is divided by the number of establishments within the industry to adjust for differences in the number of establishments across industries.

There are an additional 31 industries in SIC 34-47 which are excluded because of inadequate data on their material inputs.

[5] Value added/Pounds of Metal is measured in units of dollars/pound. Pounds of Metal/Establishment is measured in units of millions of pounds/establishment.

[6] This regression result is estimated with data aggregated at the three digit SIC level, and is not shown in Table , which gives results for data aggregated at the four digit SIC level.

[7] Industries in the sample account for almost 90 percent of the total value added in the "universe" of metalworking industries that are considered.