Flexible Technology and Industrial Structure in the U.S.*

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ABSTRACT. This paper analyzes the development over the postwar period of output, employment, and the number of plants in manufacturing in the United States. It is shown that the distribution of flexible technology in the form of machine tools (NCMTs) shifted markedly toward small plants during the 1980s. It is found that the probability of adoption and the penetration rate of NCMTs are higher in large than in small plants, even though the number of NCMTs per worker is much higher in small plants. This apparent paradox is explained. It is also suggested that the shift of output towards smaller plants is correlated with the increased use of flexible technology, and that this reflects changes in the division of labor among plants of various sizes, as well as changes in the composition and organization of production in large plants.

1. Introduction

In a previous paper in this Journal it was shown that average plant size (measured by employment) has tended to decline in manufacturing in most industrial countries since the early 1970s (Carlsson, 1989a). This finding has been confirmed in several subsequent studies (see e.g. Storey and Johnson (1990) for the United Kingdom; Loveman and Sengenberger (1991) for the U.S., Japan, France, Germany, Italy, and the U.K.; and Thurik (1990) for the Netherlands).

The Carlsson (1989a) paper proposed the hypothesis that the shift towards smaller plants could be explained at least in part by the emergence of new, flexible technology which offers greater benefits to small than to large plants, and which helps *all* adopting plants to reduce employment. At the same time, it was argued, the trend towards product differentiation makes it difficult to keep highly dedicated (specialized) equipment, such as transfer machines, operating at full capacity. Thus, new manufacturing technologies and changing market conditions have led to a shift of production to small plants with more flexibility and lower total employment.

Subsequent research has provided support for that hypothesis. Several econometric studies have found that the use of flexible manufacturing technologies tends to be negatively associated with plant size. For example, Acs, Audretsch, and Carlsson (1990 and 1991) found that the change in average plant size in the U.S. engineering industries in the 1970s and early 1980s was negatively affected by the change in the share of machine tools accounted for by numerically controlled (NC) machines that represent new, flexible manufacturing technologies. Similarly, a study on the determinants of flexible automation in the U.S. engineering industries found a negative impact of average plant size on the diffusion rate of flexible automation technologies (Taymaz, 1991a and b; see also Diwan, 1989). It should be noted that these studies are based on data at the industry level. In other words, they show that *industries* with small average plant size tend to be equipped with more flexible automation equipment that those with large plant size.

On the other hand, there have also been several econometric studies on the diffusion of NC machine tools (NCMTs) at the *firm or plant level* (Romeo, 1975 and 1977; Globerman, 1975; Liberatore and Titus, 1986; Lintner *et al.*, 1987; Cainarca *et al.*, 1990; and Kelley and Brooks, 1990). Most of these studies have found a *positive*

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coefficient for the variable measuring plant size. Since the dependent variable generally used is a binary variable taking on the value one if a given establishment is a user of NC machine tools, and zero otherwise, it measures the probability for firms to adopt NC machines. *Ceteris paribus*, this probability is greater, the more machine tools the plant has and the greater the variety of machine tools used, i.e. the larger the plant is. Thus, for example, Ehrnberg and Jacobsson have shown that only 8% of German plants with less than 20 employees used NCMTs in 1989, while the corresponding percentage in plants with more than 500 employees was 81% (Ehrnberg and Jacobsson, 1991). But the *probability of adoption* should not be confused with the *intensity* (the number of NCMTs per employee) or the *penetration rate* (the share of NC machine tools in the total stock of machine tools). Since they measure different things, it is quite possible that these various indicators diverge. In particular, it will be demonstrated below that the probability of adoption and the penetration rate of NCMTs are higher in larger plants than small, even though the number of NCMTs per worker is dramatically higher in small plants.

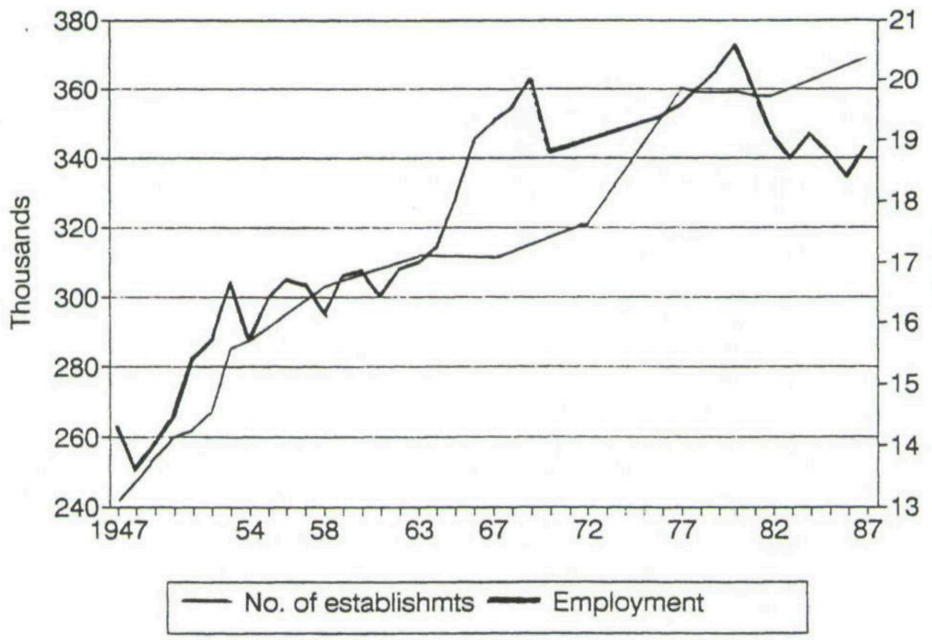
There are two purposes of this paper. One is to explain this apparent paradox. The other is to spell out more clearly the hypotheses already referred to concerning the linkages between flexible technology and the changing industrial structure in United States manufacturing industries, as well as the underlying reasons for these changes. What emerges is essentially a set of hypotheses. To the extent possible, we rely on available data to support our argument; nevertheless, several parts of the story need to be subjected to further analysis and empirical testing.

We begin by reviewing the changes in average plant size over the postwar period in the United States (Section 2) by looking at data on the development of output, employment, and the number of plants in manufacturing. We then analyze these changes with regard to changes in manufacturing technology. Thus, in Section 3, we present data on the distribution of machine tools by plant size in U.S. engineering industries. We also analyze how the distribution of flexible automation equipment as represented by NCMTs has changed over time. In Section 4 we explain why the penetration and adoption rates for NCMTs are higher in large plants than small, even though the number of NCMTs per worker is higher in small plants. Some hypotheses concerning the changing distributions of flexible technology and plant size are presented in Section 5. Our results are summarized in Section 6.

2. The development of average plant size in the United States, 1947—1987

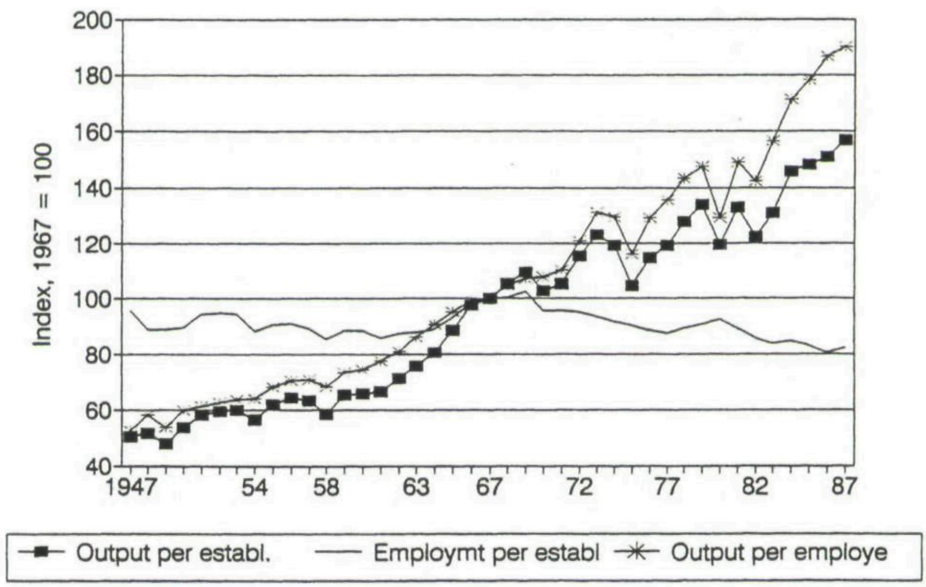
Plant size can be measured either by employment or by some indicator of output. Average plant size (APS) as measured by employment is, of course, a ratio; it depends on both the numerator (number of employees) and the denominator (number of establishments). Figure 1 shows the development of employment (right scale) and the number of establishments (left scale) in U.S. manufacturing industry during the postwar period (1947—1987). From the end of World War II until the mid-1960s, the number of plants increased at about the same rate as employment. Thus, average plant size was essentially unchanged. In the late 1960s there was a sudden and sharp increase in manufacturing employment, while the number of establishments actually fell somewhat and then increased only modestly. The result was an increase in plant size during the period 1964—69. Then came a sharp decline in employment and soon thereafter (beginning in 1973) a dramatic rise in the number of establishments, resulting in a steady decline in average plant size during 1969—77. During the most recent decade, the rate of increase of the number of establishments has again become fairly modest, while manufacturing employment has fallen after attaining an all-time high in 1980.

The resulting impact on APS (in terms of employment) is shown in Figure 2 for the entire postwar period. The Figure also shows output per establishment (an index of manufacturing output, divided by the number of establishments) and output per employee (i.e., a measure of labor productivity). While APS in terms of employment has declined by about 20 percent during the last two decades, it has clearly increased (by more than 50 percent) in terms of output, except for interruptions during 1973—77 and 1979—84; the increase was particularly sharp during the period after 1982.



Source: U.S. Bureau of the Census, *Census of Manufactures*, 1987.

Fig. 1. Employment and number of plants in U.S. manufacturing, 1947—87.



Source: U.S. Bureau of the Census, *Census of Manufactures*, 1987.

Fig. 2. Productivity and plant size in U.S. manufacturing, 1947—87.

The development of output per establishment closely reflects that of labor productivity. From 1947 to 1960, labor productivity increased at a modest rate. It increased steadily and rapidly from 1960 to 1973. It fell sharply during the first oil crisis in 1974—75 and then again during the second oil crisis in 1979. With the exception of a brief interruption in 1982 (a recession year), it increased steadily, and at a rate never seen previously during the postwar period, until 1987.

This simple analysis raises at least two sets of questions. First, were the increases in productivity and output per plant distributed evenly across the whole manufacturing sector — or were there differences among industries and among plants of different sizes? For example, did employment drop in plants of all sizes, or was the reduction concentrated to a few large plants? A series of papers by Leonard (1985, 1987 and 1992) for the United States and Blanchflower, Millward and Oswald (1991) for the United Kingdom have shown that employment decline has tended to be greatest in the largest plants; the existence of trade unions seems to have had particularly harmful effects on employment growth. Dunne, Roberts and Samuelson (1988, 1989a and b) report that small U.S. plants have higher failure rates as well as higher growth rates than large plants if they survive at all; large multi-unit plants have both lower failure rates and higher growth rates, if successful, than large single-unit plants, while the latter have negative average growth rates even when they survive. (1989b, p. 695) These results are consistent with the finding that the small-firm (less than 500 employees) share of sales increased between 1976 and 1986 from 20% to 25% in manufacturing (Acs and Audretsch, 1990, p. 4) and from 30% to 40% in engineering industries (Acs, Audretsch, and Carlsson, 1990, p. 145).

Secondly, what are the *causes* of these changes? In particular, what are the connections between changes in plant size and the diffusion of new flexible technology? This is the question to which we now turn.

3. Changes in the use of machine tools by plant size

Because of the characteristics of numerically controlled machine tools (NCMTs) and their use as part of (or at least in conjunction with) flexible manufacturing systems (FMS), it is reasonable to use the relative frequency of NCMTs as an indicator of the degree of flexible automation in various industries.[1] In this section, we present data on the use of NC machine tools in the U.S. engineering (or metalworking) industries. The data were collected by the *American Machinist* (AM, 1978; 1983; 1989).[2] The focus of our analysis is on the engineering industries, since these are the industries where metalcutting machine tools are primarily used.

There are several possible reasons why increased use of new flexible technologies may be associated with declining average plant size: i) If the use of flexible technologies — represented by NC machine tools — increase at the same rate in all size classes of plants, the observed shift in output towards small and medium size plants would yield this result. ii) If the use of NC machine tools is concentrated in small and medium plants, the output shift would lead to the observed result even if there were no change in NC machine tool use in any size class. iii) The observed result would be obtained *a fortiori* if the intensity of NC machine tool use increased more rapidly in small plants than in large ones. iv) However, even if the use of NC machine tools should increase more in large plants, a sufficiently strong shift in output would lead to a negative association between flexible technology and plant size. Then the question becomes, which one(s) of these hypotheses is (are) true?

We begin by examining aggregate machine tool data in order to see whether or not the reduction in average plant size is accompanied by a shift in the distribution of machine tools. Table I shows the distribution of the stock of metalcutting machine tools as well as numerically controlled metalcutting machine tools[3] in the U.S. engineering industries in 1983 and 1989. (The distribution of machine tools in 1978 was very similar to that in 1983, but no breakdown of NCMTs is available for that year.) The table shows that the machine tool stock has clearly shifted into smaller-size plants. The total stock of metalcutting machine tools increased by about 10% between 1983 and 1989, while the stock of NCMTs more than doubled. What is perhaps more surprising is that the number of non-NC (i.e., conventional) machine

TABLE I
Distribution of metalcutting machine tools in U.S. engineering industries by plant size, 1983 and 1989

Plant Size (Number of Empl.)	1989				1983			
	Numer. contr.		Total metalcutting		Numer. contr.		Total metalcutting	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
1–19	36,430	18	433,902	23	5,743	6	119,480	7
20–99	88,346	43	833,994	45	31,623	33	602,903	35
100–499	47,767	23	396,818	21	28,886	31	538,831	32
> 500	31,925	16	206,039	11	28,120	30	441,619	26
Total	204,468	100	1,870,753	100	94,372	100	1,702,833	100

Source: *American Machinist* (1983 and 1989).

tools was actually *reduced* by more than 50% in the largest plants while it quadrupled in the smallest plants. The number of NCMTs increased in all plant sizes, quite dramatically in small plants but only modestly in large plants. As a result, while 42% of all machine tools were in plants with fewer than 100 employees in 1983, this share jumped to 68% in 1989.[4] Although there may be some errors due to sampling and estimation problems, the shift towards small plants is indisputable.

On the basis of Table I it is possible to calculate the penetration rate in each size category.[5] The results are shown in Table II. In spite of the much more rapid increase of NCMTs in small plants, the penetration rates (share of NCMTs in the total stock of machine tools) were not only higher in large than in small plants in both years but also increased faster in large than in small plants. In other words, the penetration rates increased monotonically with plant size; the technology diffused within all size groups; and the rate of diffusion also increased monotonically with plant size!

TABLE II
Penetration rates of NC machine tools by plant size, 1983 and 1989

Plant size	% NC 1983	% NC 1989	1989/1983
1–19 employees	4.8	8.4	1.75
20–99 employees	5.2	10.6	2.04
100–499 employees	5.4	12.0	2.22
> 500 employees	6.4	15.5	2.42

Source: *American Machinist* (1983 and 1989).

How is it possible that the number of NCMTs increased more than sixfold in the smallest plants and by only 14 percent in the largest plants, and yet the penetration rate increased faster in large than in small plants? At one level of analysis (a deeper level will be pursued in the next Section of the paper), the answer is simple: the penetration rate increased faster in large plants primarily because the denominator (total metalcutting machine tools) was cut in half, not because the number of NCMTs increased. Conversely, the penetration rate in the smallest plants increased more slowly than in large because the total number of metalcutting machine tools also increased (by a factor of 3.6).

Table III tells the story in more detail. In plants with less than 100 employees, the number of NCMTs increased by 237% while non-NC machines increased by "only" 67%. In larger plants, the number of *every* kind of non-NC machines declined while every type of NC machines (except drilling machines which were probably substituted by NC machining centers) increased. Thus, there was a clear substitution of NC for non-NC machines of the same type. In large plants, the new NC machines apparently replaced several non-NC machines, thus leading to the sharp decline in non-NC machine tools. The same kind of substitution seems to have taken place in small plants as well, but there the growth rate was sufficient to generate an increase in the number of

TABLE III
Number of metalcutting machine tools by plant size, 1983 and 1989

	Plants with 1—99 employees				Plants with 100 or more employees			
	Number of units		Change between 1983 and 1989		Number of units		Change between 1983 and 1989	
Type of equipment	1989	1983	Units	Percent	1989	1983	Units	Percent
NC turning machines	42,595	12,360	30,235	244.6	31,482	20,992	10,490	50.0
Non-NC turning machines	223,725	142,526	81,199	57.0	106,632	189,801	(83,169)	−43.8
NC boring machines	4,793	1,575	3,218	204.3	5,895	3,489	2,406	69.0
Non-NC boring machines	24,902	12,937	11,965	92.5	12,470	27,525	(15,055)	−54.7
NC drilling machines	5,977	2,930	3,047	104.0	4,406	5,063	(657)	−13.0
Non-NC drilling machines	188,827	117,691	71,136	60.4	85,796	163,762	(77,966)	−47.6
NC machining centers	35,647	8,814	26,833	304.4	17,938	15,189	2,749	18.1
NC milling machines	19,163	8,734	10,429	119.4	9,097	7,195	1,902	26.4
Non-NC milling machines	161,133	100,367	60,766	60.5	59,713	118,112	(58,399)	−49.4
NC gear-cutting machines	346	—	346	—	458	—	458	—
Non-NC gear cut & finish mach.	18,055	9,660	8,395	86.9	10,650	25,174	(14,524)	−57.7
NC grinding machines	7,441	707	6,734	952.5	5,306	1,569	3,737	238.2
Non-NC grinding machines	285,441	159,640	125,801	78.8	136,659	223,387	(86,728)	−38.8
Honing, lapping, polishing mach.	30,833	19,196	11,637	60.6	17,704	31,430	(13,726)	−43.7
Station-type metalcutting mach.	4,991	1,581	3,410	215.7	8,259	12,007	(3,748)	−31.2
Broaching machines	10,298	5,022	5,276	105.1	6,400	11,483	(5,083)	−44.3
Tapping machines	23,272	12,741	10,531	82.7	8,678	15,398	(6,720)	−43.6
Threading machines	6,720	5,779	941	16.3	2,813	5,924	(3,111)	−52.5
Cutoff & sawing machines	146,271	86,095	60,176	69.9	58,383	83,012	(24,629)	−29.7
Waterjet machines	1,012	—	1,012	—	243	—	243	—
NC laser & thermal cutting units	2,979	335	2,644	789.3	1,488	699	789	112.9
Non-NC thermal cutting mach.	4,939	2,179	2,760	126.7	1,234	3,123	(1,889)	−60.5
Electrical machining units	12,124	5,429	6,695	123.3	6,912	7,005	93	−1.3
Other NC metalcutting machines	981	746	235	31.5	1,080	2,375	(1,295)	−54.5
Other non-NC metalcutting mach.	5,431	5,339	92	1.7	3,161	6,736	(3,575)	−53.1
Total metalcutting machines	1,267,896	722,383	545,513	75.5	602,857	980,450	(377,593)	−38.5
Total NC metalcutting machines	124,776	37,006	87,770	237.2	79,692	57,006	22,686	39.8
Total Non-NC cutting machines	1,143,120	685,377	457,743	66.8	523,165	923,444	(400,279)	−43.3

Source: *American Machinist*, 1983 and 1989.

both NC and non-NC machine tools. (Even station-type machines increased in small plants, despite the fact that they are typically associated with high-volume production. More on this later.) There can be no doubt concerning the increasing importance of flexible technologies and the declining importance of conventional production systems.

Examining the rates of change of the number of NC machine tools in small plants in Table III (the third and fourth columns), it is apparent that except for NC grinding machines and NC laser and thermal cutting machines (of which there were very few in the early 1980s), the highest growth rates are noted for NC machining centers (+304%) and NC turning machines (+245%). It is noteworthy that both of these types of machines actually declined in price (by 4% and 22%, respectively), while the price of other NCMTs increased by 70% between 1983 and 1989.[6] This provides at least part of the explanation for the rapid increase of these types of NCMTs.

On the basis of Table III it is also possible to calculate the relative intensity of various types of machine tools in small and large plants. This is done by dividing the number of units of each type in small plants by the corresponding number in large plants. The results are shown in Table IV. Using the ratio for "Total metalcutting machines," one can then calculate an index of relative use. If this index is less than one, the smaller plants have a smaller share of the total stock of such machines than they do of all machine tools. The index for 1989 has particularly low values for Station-type metalcutting machines, NC gear-cutting machines, NC boring machines, and Other NC metalcutting machines. The first two (and possibly three) of these types of machines are typical of large-volume operations. The index is particularly high for specialty machines such as Waterjet machines and Non-NC thermal cutting machines. But due to the absolute decline in the number of non-NC machine tools in large plants between 1983 and 1989, the ratio of NC to non-NC machine tools in large plants rose sufficiently to cause a decline in the small/large plant ratio for Total NC metal-cutting machines between 1983 and 1989, despite the rapid diffusion of NCMTs in small plants.

Further insight may be gained by examining the distribution of machine tools in relation to employment. Such an analysis is made in Table V, where data on the number of production workers (by plant size) from the Census of Manufactures for 1982 and 1987, respectively, are matched against the American Machinist inventories of NCMTs in 1983 and 1989. As shown in the Table, the total number of production workers in the engineering industries (SIC industries 34—38)

TABLE IV
Relative machine intensity by type of machine in small and large plants, 1983 and 1989

Type of equipment	1989 Small/large plant ratio	1989 Small/large plant share relative to total mach.	1983 Small/large plant ratio	1983 Small/large plant ratio relative to total mach.
NC turning machines	1.35	0.64	0.59	0.80
Non-NC turning machines	2.10	1.00	0.75	1.02
NC boring machines	0.81	0.39	0.45	0.61
Non-NC boring machines	2.00	0.95	0.47	0.64
NC drilling machines	1.36	0.65	0.58	0.79
Non-NC drilling machines	2.20	1.05	0.72	0.98
NC machining centers	1.99	0.94	0.58	0.79
NC milling machines	2.11	1.00	1.21	1.65
Non-NC milling machines	2.70	1.28	0.85	1.15
NC gear-cutting machines	0.76	0.36	—	—
Non-NC gear cut & finish mach.	1.70	0.81	0.38	0.52
NC grinding machines	1.40	0.67	0.45	0.61
Non-NC grinding machines	2.09	0.99	0.71	0.97
Honing, lapping, polishing mach.	1.74	0.83	0.61	0.83
Station-type metalcutting mach.	0.60	0.29	0.13	0.18
Broaching machines	1.61	0.77	0.44	0.59
Tapping machines	2.68	1.28	0.83	1.12
Threading machines	2.39	1.14	0.98	1.32
Cutoff & sawing machines	2.51	1.19	1.04	1.41
Waterjet machines	4.16	1.98	—	—
NC laser & thermal cutting units	2.00	0.95	0.48	0.65
Non-NC thermal cutting mach.	4.00	1.90	0.70	0.95
Electrical machining units	1.75	0.83	0.78	1.05
Other NC metalcutting machines	0.91	0.43	0.31	0.43
Other non-NC metalcutting mach.	1.72	0.82	0.79	1.08
Total metalcutting machines	2.10	1.00	0.74	1.00
Total NC metalcutting machines	1.57	0.74	0.65	0.88
Total Non-NC cutting machines	2.19	1.04	0.74	1.01

Source: see Table III.

TABLE V
Distribution of production workers and machine tools by size of plant in U.S. engineering industries, 1982/83 and 1987/89

	Plants with		
1982/83	1–99 empl.	> 100 empl.	Total
Production workers in SIC 34–38, thousands (1982)	1,308.4	3,744.0	5,052.4
Percent	25.9	74.1	100.0
Number of NCMTs (1983)	37,366	57,006	94,372
Percent	39.6	60.4	100.0
Number of non-NCMTs (1983)	685,377	923,444	1,608,821
Percent	42.6	57.4	100.0
NCMTs per 1000 production workers	28.6	15.2	18.7
Non-NCMTs per 1000 production workers	523.8	246.6	318.4
1987/89			
Production workers in SIC 34–38, thousands (1987)	1,311.1	3,620.0	4,931.1
Percent	26.6	73.4	100.0
Number of NCMTs (1989)	124,776	79,692	204,468
Percent	61.0	39.0	100.0
Number of non-NCMTs (1989)	1,143,120	523,165	1,666,285
Percent	68.6	31.4	100.0
NCMTs per 1000 production workers	95.2	22.0	41.5
Non-NCMTs per 1000 production workers	871.9	144.5	337.9

Sources: *American Machinist*, 1983 and 1989.
U.S. Bureau of the Census, *Census of Manufactures*, 1982 and 1987

dropped by about 120,000 persons between 1983 and 1989. The larger plants actually lost slightly more than that number, while smaller plants gained slightly (confirming the findings mentioned earlier). Because of the sharp increase in the number of NCMTs in smaller plants, the whole distribution shifted dramatically, as noted earlier. As a result, the smaller plants accounted for more than two-thirds of the conventional machine tools in 1989, compared with 43 percent in 1983.

Table V also shows that the number of numerically controlled machine tools per production worker trebled in small plants between 1983 and 1989 (from 28.6 to 95.2 per 1000 production workers), while it increased by a more modest 44% in large plants. Meanwhile, the number of conventional machine tools per production worker increased by 66 percent in small plants and *fell* by 59 percent in large plants. It can also be seen that the number of NCMTs was almost twice as high (28.6/15.2 = 1.9) in small plants as in large ones in 1983; by 1989 the ratio was 4.3:1. But the relative intensity of conventional machine tools in small compared to large plants increased even more dramatically: from a ratio of 2.1 : 1 in 1983 to a ratio of 6.0 : 1 in 1989 – again due in large part to the very great decline in the number of conventional machine tools in large plants.

Even if these data are subject to measurement and sampling errors, it is quite clear a) that the total number of machine tools per worker is much higher in small than in large plants; this is true particularly for conventional machine tools; b) that this "intensity" has increased impressively in recent years in small plants for NCMTs and even more so for conventional machine tools; at the same time, the number of NCMTs per worker has increased only modestly in large plants, while there has been a large reduction in the number of conventional machine tools.

In terms of the hypotheses stated on p. 196 above, it is the third one that is supported by the data: While the number of NCMTs per employee was probably higher in large than in small plants during the 1960s and 70s, it was clearly higher in small plants by 1983 and overwhelmingly so by the end of the 1980s.

It should be pointed out, however, that the data used here refer to the *number* of machines, not their value or productive capacity. To the extent that the NC machines used in large plants are larger, faster, more complex and productive than those in small plants, the ratios reported here overstate the differences between plants of different sizes. But while the differences in capacity between large, customized machines and small, general-purpose machines are not likely to be as large as 4 : 1, more research is clearly needed on the types of machine tools and the manner in which they are used in small and large plants.

The overall picture that emerges is the following. Numerical control was developed in the 1950s and applied commercially in the 1960s and 70s primarily by large companies manufacturing a variety of complex parts with extremely great precision requirements (Carlsson, 1984, p. 103). This is reflected in the large shares of large plants of NC machine tools in the earlier years. It was only after the Japanese had developed soft-wired NC systems in the mid-1970s that NC machine tools became sufficiently cheap, flexible, and easy to use to be adopted extensively by small plants. (Jacobsson, 1986; Carlsson, 1989b.) For the first time, automation became feasible even in small and medium-size plants. Thus, the number of NC machine tools used in small plants (with 1—99 employees) was only around 10,000 in 1978 but reached 37,000 by 1983 and 125,000 by 1989. At the same time, the number of NCMTs rose in large plants also, as new and more productive machines replaced both conventional machines and older NC machines.

4. Resolving the paradox

We return now to a more profound explanation of the (apparent) paradox stated earlier: the observation that the penetration rates of NCMTs increased faster in large than in small plants during the 1980s, even though the NCMT intensity was increasing faster in small plants. What follows is a hypothesis which needs to be tested empirically.

As already indicated, there has been a tendency for large plants to shrink in terms of employment. Tables I and III show that large plants have also dramatically reduced the number of non-NC metalcutting machine tools while increasing their NCMTs slightly. This suggests a dramatic increase in productivity in large plants — which is also consistent with Figure 2. In other words, a few NCMTs have replaced a large number of older, conventional machine tools while also reducing employment. This has certainly increased the penetration rate of NCMTs.

The story appears to be different in small plants. First of all, their employment has grown, and so has their stock of machine tools, both conventional and NC, but with much higher growth rates for the latter. According to Table V, there is now almost one machine tool per worker in small plants ($0.0952 + 0.8719 = 0.9671$), while there is only 0.1665 per worker in large plants. This, in turn, suggests that there are substantial differences in the way machine tools are used in small and large plants. Our hypothesis is that the rapid increase in NCMTs in small plants can be attributed in large part to their being used in the mainstream of production, whereas in large plants, many stand-alone NCMTs tend to be used for more specific tasks either supplementary to the main production lines or in special off-line functions (e.g. tooling and maintenance).

Several things point in this direction. As has been shown by Kelley and Brooks (1990) and others, high labor cost is one of the most important determinants of adoption of flexible automation. Between 1983 and 1989, the employment cost index for manufacturing workers rose by 26%.[7] At the same time, the average machine tool increased in price by 47.4%. However, the price of numerically controlled machine tools increased by only 15%, while that of NC lathes *fell* by 22% and that of NC machining centers by 4%. Thus, there were significant price incentives to substitute NC machine tools for labor and also to substitute NCMTs for conventional machine tools in connection with replacement.

What happened in response to these incentives is that large plants reduced their stock of conventional machine tools by 400,000 units, reduced their employment by 124,000 workers, and increased their stock of NCMTs by 22,000 units. The reduction in employment may in fact have shifted some plants to smaller size categories. Meanwhile, small plants kept about the same labor force, increased their stock of conventional machine tools by two-thirds and their NCMTs by more than 200%.

But why did small and large plants respond so differently to these incentives? Shouldn't the price incentives be equally powerful for both small and large plants? In our view, the answer lies in the different ways in which NCMTs are used in small and large plants. If the price drops for a machine which is likely to be heavily used directly in production, the incentive to buy it is much greater than if that machine is likely to be used off-line, i.e., resulting in less labor substitution. The fact that it is the most versatile NC machines (NC machining centers and lathes) that have increased the most rapidly in small plants while these plants are still lagging behind large ones in the application of more specialized NC machines (e.g. gear-cutting and boring machines) suggests that different machines are used in large and small plants and that there are differences in *how* they are used. This hypothesis needs to be tested in further empirical work.

5. The reasons behind the changing distributions of flexible technology and plant size

There are many possible explanations for the increase in NC machine intensity of all plants, but particularly small ones during the 1980s on the one hand, and the shift in output towards smaller plants on the other. In our view, these changes are interrelated. What follows is essentially a hypothesis, parts of which are supported by currently available data, other parts requiring further data and analysis.

The most important motivating forces are rooted in three major changes taking place in the world economy in the past two decades. These changes in the economic environment are i) intensified *global competition* as a result of the developments in transportation, information, and communication technologies and the resulting increased integration of the world economy; ii) a high degree of *uncertainty* reflecting a significant growth slowdown in all industrial countries triggered by the oil price shocks in the 1970s, exacerbated by volatility of exchange rates and reflected in high rates of interest, inflation, and unemployment; and iii) intensified *fragmentation* due to growing consumer demand for differentiated products, inducing firms to increase their emphasis on product differentiation.

Each of these changes has engendered micro-level responses as enterprises have been subjected to increasing pressure to adjust to the new conditions. Increased global competition tends to lead to increased specialization (concentration on core business areas), while uncertainty and fragmentation force firms to increase their flexibility and search for new ways to differentiate their products.

5.1. *Specialization*

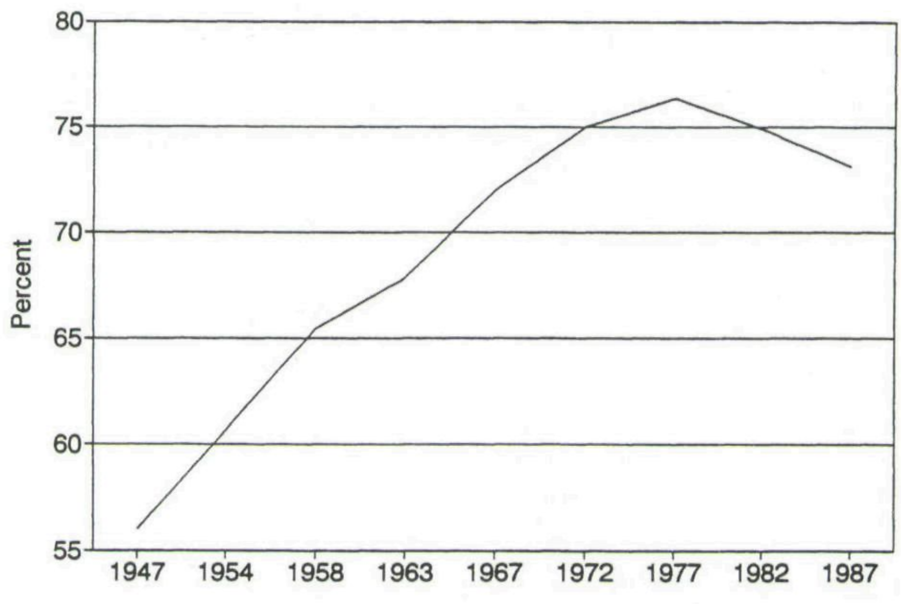
Specialization (which refers to both vertical disintegration and horizontal "de-glomeration") has increasingly been regarded as i) a way to cut overheads and fixed costs, ii) a way to reduce uncertainty,[8] iii) a means of accessing cheap labor sources,[9] and iv) a way to obtain new sources of supply of high quality, specialized inputs. There are various observed forms of specialization or vertical disintegration:

1) *Decentralization*: large plants are broken up, but new small plants are retained under the same ownership.
2) *Subcontracting*: specific parts and components manufactured and certain specialized processing performed in-house are increasingly obtained from specialized plants by forming semi-permanent relations (not necessarily involving ownership).
3) *Other outsourcing*: parts and components are no longer manufactured in-house but are purchased from the market without any long-term relations with the producer.

As pointed out in a previous study (Carlsson, 1989a), there is increasing evidence that firms are becoming smaller and less vertically integrated. Thus, for example, the largest 500 industrial companies in the United States ("The Fortune 500") lost some of their share of manufacturing employment as well as output during the 1980s (*ibid.*, p. 28). There is plenty of anecdotal evidence supporting this view. The trend towards specialization and vertical disintegration in the U.S. is shown also by the rapid growth of the business services industry. This sector (SIC 73) had the highest average annual employment growth in 1969—1984 amongst the 2-digit SIC sectors (Kutscher and Personick, 1986, p. 9). Firms can gain flexibility and reduce costs by using contractors to supply certain types of services rather than hiring permanent employees.

In some cases, the end result of vertical disintegration is to achieve a flexible network of firms. Individual firms in this network may become highly specialized while the network as a whole is flexible (Carlsson and Stankiewicz, 1990). Saxenian (1991) provides several examples of such production networks in Silicon Valley. Similar networks of specialized firms have long been developing in Japan (for a historical analysis, see Imai, 1989). This is partly a result of substantial subcontracting of business between large and small firms. In the late 1980s, some two-thirds of small and medium sized enterprises (with less than 300 employees) were subcontractors to large enterprises and accounted for one-third of the total shipments by small and medium-sized manufacturers (KJS, 1988, p. v). Similar evidence is available for other countries.

There are no specific U.S. data that can be used to determine definitively which form of vertical disintegration is the most important. However, data on multi-unit and single-unit companies can shed light on this issue. The share of multi-unit companies in U.S. manufacturing employment increased throughout the postwar period until the late 1970s. But after 1977, the share of multi-unit companies declined for the first time. See Figure 3. This suggests that subcontracting and outsourcing have become more important forms of disintegration in recent years. The recent literature on subcontracting and supplier-customer relations in industry provides growing support for this hypothesis. (See Nishiguchi, 1990, for an excellent litera-



Source: U.S. Bureau of the Census, *Census of Manufactures. Type of Organization* (Subject Series, MC87-S-5), 1987.

Fig. 3. Share of multi-unit companies in U.S. manufacturing employment, 1947—1987.

ture survey; see also Helper (1987, 1990a and b) and references therein.) Working closely with a limited number of suppliers is an integral part of so-called "lean production" which is now spreading from its origin in the Japanese auto industry to the auto producers and other businesses in America and Europe. (Womack *et al.*, 1990.)

It is interesting to note that subcontracting is also the primary form of small business development in the Japanese manufacturing industry which already has a very high subcontracting rate. The share of subcontracting businesses in small and medium size enterprises (employing less than 300 employees) increased from 53.3% in 1966 to 58.7% in 1971 and 65.5% in 1981 (MITI, 1983: 47). Consequently, the number of subcontracting businesses increased by 62% in this period, whereas the number of independent (non-subcontracting) small and medium size businesses remained about constant.

5.2. *Increased flexibility*

While networking may be seen as a way for firms to deal with uncertainty and to achieve flexibility by changing their relations with external units, firms also must find ways to respond internally as well. Under the pressure of uncertainty, enterprises are intensifying the search for greater flexibility (Kanawaty *et al.*, 1989, p. 294). A typical response of engineering firms has been to strive to increase their operational flexibility (the ability to change sequencing, scheduling, etc., in the short term) as well as their tactical flexibility (ability to change the rate of production, product mix, and product design in the medium term)[10] by investing in computerized, flexibly automated technologies. NC machine tools are the main component of these technologies.

In large plants, the adoption of NC machine tools is being driven by the ability of these machines to reduce the cost of manufacturing i) complex products (products with complex cutting shapes, large number of machining operations, etc.), and ii) a closely related family of products. NC machine tools are advantageous in the manufacturing of complex products because they can control the movements of cutting tools and/or work pieces rapidly and accurately. (Manual controls can be more flexible and economic for batch manufacturing of simple products.) However, the fixed costs associated with complex products are often high. For example, the design costs of a complex part may be so high that a high level of *cumulative* output is necessary for cost effectiveness, even if the equipment used in its manufacture is highly flexible. Although set-up time is short in NC machine tools through the use of software, initial programming and debugging of programs may take considerable time, especially for the machining of complex parts.

For these reasons, complex NC machine tools and other types of flexible automation equipment may be beneficial only when a large number of parts sharing the fixed costs of design, programming, etc., are manufactured in small batches. The manufacture of a variety of complex parts is typical of many large-scale plants, such as those manufacturing aircraft, construction machinery, and engine and turbine plants. It is not surprising, therefore, that these plants were the early adopters of NCMTs.

But when the Japanese introduced microcomputer-based numerical controllers in the mid-1970s, two important things happened. On the one hand, the programmability and therefore flexibility of NCMTs increased dramatically. This benefitted all potential users, both large and small. On the other hand, cheaper and more flexible numerical controllers in combination with other changes led to mass production of NCMTs, resulting in drastically reduced prices. For example, the price of an NC lathe dropped from 8.3 times that of a conventional lathe in 1974 to 4.9 in 1975 and 2.9 in 1981. (Ehrnberg and Sjöberg, 1992, p. 16.) This, in turn, opened up a vast new market, namely small and medium-sized metalworking plants. Suddenly, automation came within reach of small producers for the first time. They were no longer handicapped to the same extent as earlier in competing for business with large firms. This strengthened the tendency towards specialization on the part of large firms which now found it more advantageous to subcontract or outsource components to smaller plants and firms.

5.3. *Product differentiation*

Another factor contributing to changing working relationships and division of labor between large and small plants has to do with increased demand for product differentiation. By increasing the use of modular design (each product or part consisting of a number of modules, and each module being available with a variety of features), it is possible to achieve an almost infinite variety of characteristics of the final product. The manufacturer then has the option of producing everything in-house or subcontracting or outsourcing all or some of the components and/or modules. The tendency in recent years seems to have been for the original manufacturer to focus on certain key components while subcontracting or outsourcing others. In case of the former, the subcontractor may very well have on-line electronic exchange of information (specifications, drawings, etc.) with the contractor, making it possible to make design changes quickly and cheaply and to coordinate production via just-in-time delivery systems. Such an arrangement allows increased specialization for both the original manufacturer and his suppliers, making it possible to exploit economies of scale for all parties involved.

It is noteworthy that the increase in the number of variants came around 1980, just when the "new" NCMTs made their breakthrough. In the U.S. authomobile industry, for example, the number of models offered by U.S. manufacturers fell during the 1970s (from 375 in 1970 to 247 in 1979), but it increased during the 1980s (to 313 in 1986). (Carlsson, 1989a, p. 34.) Similarly, the number of models sold by Japanese auto manufacturers increased from 47 in 1982 to 84 in 1990. (Womack *et al.*, 1990, p. 119.) The proliferation has continued.

5.4. *New division of labor between large and small plants*

The preceding discussion has suggested that there is a whole set of mutually reinforcing changes in the organization of manufacturing: large plants moving away from mass production into batch production: increased specialization causing large plants to shrink and allowing small manufacturers to shift towards higher volumes of production; subcontracting, outsourcing, and networking involving a new division of labor between large and small firms and between suppliers and customers.

In the 1980s, small plants appear to have prospered more than large plants under these new arrangements. Given their rapid accumulation of new NCMTs, and in view of the discussion in the previous Section, it would not be surprising if the productivity gains of small plants were found to be greater than those of large plants. While systematic studies are lacking, anecdotal evidence abounds. For example, the installation of a flexible manufacturing system (FMS) formed by 43 NC machines in the Yamazaki Machinery plant reduced the labor requirement from 195 to 39 (Usui, 1984. For similar cases, see Jaikumar, 1986).

If the type of change in the division of labor is really taking place as suggested here, it should be observable on industry data. Such data are scanty, but in order to at least indicate the nature of the data and analysis required, we show in Table VI a comparison of data for a group of "final products" and "parts and components" industries at the 4-digit SIC level. While this classification is based on subjective judgement and is only illustrative, the findings reported below are not materially affected by adding or removing a few industries and can be used to get an idea about recent changes.

As may be expected, final products industries had significantly higher concentration and coverage ratios in 1977 than did parts and components industries. The APS (indicated by SIZE77 in the table) in final products industries was twice as large as that in parts and components industries, the difference being statistically significant at the 5% level. Between 1977 and 1987, the average concentration ratio was essentially unchanged in the final products industries but declined in the parts and components industries, although the difference is not statistically significant. The average coverage ratio for parts and components industries increased much faster than for final products. In other words, the fraction of parts and components produced by parts and components industries grew rapidly. Moreover, the average change in employment in final products industries was negative (−8.9%), while it remained unchanged in parts and components industries, but the difference is not statistically significant. The increase in the number of firms and establishments was also greater in parts and components industries; in both cases the differences are highly

TABLE VI
Basic data on final product and parts and components industries

	CONC77	COV77	SIZE77	CCONC	CCOV	CEMP	CFIRM	CEST	CSIZE
Final products (n = 35)									
Mean	48.57	87.34	308.44	0.14	2.31	−8.87	−3.06	−1.80	17.39
Std dev	21.69	16.36	460.56	9.18	4.86	29.06	161.85	183.77	344.84
Parts & components (n = 27)									
Mean	39.59	85.04	164.71	−1.70	7.52	0.44	82.63	93.22	−27.56
Std dev	19.28	8.78	151.72	4.30	17.41	28.90	160.41	163.01	55.12
Difference in mean values	8.98	2.30	143.73	1.84	−5.21	−9.31	−85.69	−95.02	44.95
t-value	1.72**	0.71	1.73**	1.05	−1.51*	−1.25	−2.08**	−2.15*	0.76

Notes: ** (*) means the difference in means is statistically significant at the 5% (10%) level, one-tailed test.
Variable definitions: CONC77: concentration ratio in 1977; COV77: coverage ratio in 1977; SIZE77: average establishment size in 1977; CCONC: change in the concentration ratio; CCOV: change in coverage ratio; CEMP: change in the number of employees; CFIRM: change in the number of firms; CEST: change in the number of establishments; CSIZE: change in the average establishment size. All change variables refer to the period 1977—1987.
Final products industries: Turbines and turbine generator sets; Farm machinery and equipment; Lawn and garden equipment; Construction machinery; Mining machinery; Oil and gas field machinery; Elevators and moving stairways; Conveyors and conveying equipment; Machine tools, metal cutting types; Machine tools, metal forming types; Power-driven handtools; Rolling mill machinery; Textile machinery; Paper industries machinery; Commercial laundry equipment; Refrigeration and heating equipment; Household cooking equipment; Household refrigerators and freezers; Household laundry equipment; Household housewares and fans; Household vacuum cleaners; Household appliances, n.e.c.; Motor vehicles and car bodies; Truck trailers; Motor homes; Aircraft; Ship building and repairing; Boat building and repairing; Railroad equipment; Guided missiles and space vehicles; Travel trailers and campers; Tanks and tank components; Environmental controls; Instruments to measure electricity; and Surgical and medical instruments.
Parts and components industries: Cutlery; Saw blades and handsaws; Fabricated plate work (boiler shops); Iron and steel forgings; Automotive stampings; Miscellaneous fabricated wire products; Fabricated metal products, n.e.c.; Industrial patterns; Special dies, tools, jigs, and fixtures; Machine tool accessories; Ball and roller bearings; Air and gas compressors; Speed changers, drives, and gears; Power transmission equipment, n.e.c.; Carburetors, pistons, rings, and valves; Motors and generators; Semiconductors and related devices; Electronic capacitors; Electronic resistors; Electronic coils and transformers; Electronic connectors; Engine electrical equipment; Truck and bus bodies; Motor vehicle parts and accessories; Aircraft engines and engine parts; Aircraft parts and equipment, n.e.c.; and Space propulsion units and parts.
Source: Bureau of the Census, *Census of Manufactures, 1987.*

significant. Thus, the changes in general support the hypothesis suggested earlier.

Now we are in a position to re-examine the use of flexible automation equipment within the changing pattern of inter-firm relations towards increased specialization (involving both vertical disintegration and "de-glomeration") and formation of networks of closely related establishments. The low and unstable rates of growth in manufacturing and engineering industries, increased global competition, pressures for product differentiation, and the development of communication and information technologies have considerably decreased vertical integration of manufacturing and engineering plants. The intensified use of flexible automation equipment (including NC machine tools, robots, etc.) constitutes a part of firms' strategy to improve production flexibility. During the 1960s and 70s, NC machine tools were used primarily in large firms that tend to produce relatively complex products and a large variety of similar products and that try to keep high value added activities in their plants. The second major component of firms' strategies to achieve flexibility is to form a network of specialized suppliers (Womack *et al.*, 1990; Saxenian, 1991). Increased product variety is then achieved by using mostly standard, modular parts and components, and producing variants of only a few basic designs, and using multi-model and mixed-model assembly lines.

Specialized suppliers need specialized machinery, as we observe an increase in the mass production machinery intensity of small, specialized plants in the U.S. engineering industries.

6. Conclusions

In this paper, we have presented evidence that the decline in plant size (as measured by employment) which characterized manufacturing industry in most industrial countries during the 1970s, breaking the earlier increasing trend, appears to have continued during the 1980s. We have also presented data on the use of machine tools in the U.S. engineering industries. These data reveal that there has been a significant and increasing concentration of machine tools in small plants and an increase in the use of flexible automation equipment (represented by numerically controlled machine tools, NCMTs) in plants of all sizes but particularly in small plants during the period 1983—1989. One result of this is that the number of NCMTs per employee in small plants increased from 2 : 1 relative to that in large plants in 1983 to more than 4 : 1 in 1989. At the same time, the number of non-NCMTs per worker, which was also higher is small than in large plants, increased further in small plants while actually being reduced in large plants. In our view, these different developments can be explained by differences in the types of machine tools used and the manner in which they are used in large and small plants, and by different substitution processes being at work. In large plants, NCMTs substituted both conventional machine tools and labor (both of which were reduced in number), while in small plants the number of production workers remained constant while both conventional and numerically controlled machine tools (especially the latter) increased, thus essentially indicating a mechanization process. We hypothesize that this development, in turn, has to do with a new division of labor between final product and parts/components producers, and between large and small plants which has been developing in the last decade or so. The relationship between large and small plants is becoming more cooperative and network-like rather than competitive.

Notes

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[1] This hypothesis has been tested by Acs, Audretsch and Carlsson (1990 and 1991), Carlsson, Acs and Audretsch (1993), and is consistent with Carlsson (1991).

[2] The *American Machinist* surveys are conducted every five years. They are based on a questionnaire which is sent to all metalworking plants in the 48 contiguous States having 20 employees or more and to a sample of 10,000 with less than 20 employees. The response rate among the former in the 1983 survey was 24.4% and 9.6% in the latter group. Metalworking industries are defined as consisting of the following Standard Industrial Classification (SIC) industries: SIC 25 (furniture and fixtures, metal only); SIC 33 (primary metals, metalworking only), SIC 34 (fabricated metal products), SIC 35 (machinery, except electrical); SIC 36 (electrical machinery); SIC 37 (transportation equipment); SIC 38 (precision instruments); and SIC 39 (miscellaneous metal products). The survey covers only those plants within these industries in which the principal business is metalworking. The identity of plants, their SIC codes, size of employment, address, etc., are obtained mainly from the Mc-Graw-Hill Market Data File.

The AM Inventory covers data in four categories: 1) number of units of equipment by 173 types; 2) age of equipment in four categories; 3) distribution of equipment within 24 geographic areas; and 4) distribution of equipment by four plant-size groups.

For further information about the AM inventory and details of the research method, see the summary of the report published in *American Machinist* (1978, 1983, and 1989).

[3] The following discussion is focused on metalcutting (as distinguished from metalforming) machine tools. Therefore, unless otherwise stated, "machine tools" refer to "metalcutting machine tools."

[4] There is a similar shift in the use of metalforming machine tools, too. 64% of forming machines were found in plants with fewer than 100 employees in 1989. This fraction was only 39% in 1983, and 33% in 1978 (see AM, 1989: 97).

[5] We are grateful to Bennett Harrison for bringing this to our attention.

[6] Calculated on the basis of data obtained from NMTBA (1990), p. B-4. These price changes are probably the result of a combination of factors: the availability of NC on smaller and less specialized machines and consequent shift in consumption to these machines; price reductions due to a large number of machines being sold, making it possible to exploit scale economies to an unprecedented extent, and to significantly increasing pressure from imports (the import penetration rate rose from 38 to 70% for NC horizontal lathes and from 49 to 53% for NC machining centers (NMTBA, 1990, pp. A-7—A-9).

[7] Calculated on the basis of data obtained from U.S. Bureau of the Census, *Statistical Abstract of the United States, 1992* (Washington, D.C.: USGPO), p. 417.

[8] The idea here is that by specializing, the firm can acquire more expertise in the chosen field than its competitors, hence reducing uncertainty to some degree, and allowing it a relatively favorable position to deal with remaining uncertainty.

[9] In the U.S., the average wage rate in plants with less than 20 employees is around 25% lower than the rate in plants with more than 500 employees. The corresponding wage disparity is more than 50% in Japan.

[10] See Carlsson (1989c) for further discussion of various types of flexibility.

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