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Flexible technology and plant size U.S. manufacturing and metalworking industries

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Abstract

There is a long tradition in industrial organization of analyzing the characteristics of technology that are important determinants of market structure. In this paper we test and find support for the hypothesis that the application of flexible technologies has been a catalyst in shifting the plant-size distribution in U.S. manufacturing industries towards smaller average plant size.

JEL classification: L11; L2; L6; O33

1. Introduction

The size distribution of firms in manufacturing industries has shifted over time. For example, Sands (1961) found an increase in plant size for all of manufacturing between 1904 and 1947. Similarly, Scherer (1980) reported an increase in the MES (minimum efficient scale, or the smallest level of output required to attain minimum average cost) between 1958 and 1970 in the steel, cement, brewing, paint, refrigerator, and battery industries, while he found a modest decrease in bearings, shoes, and weaving. On the other hand, Blair concluded already in 1948 —but apparently prematurely—that

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the 'long-term, general, and pervasive increase in plant size throughout most industries has come to an end' and 'that as a result of new decentralizing techniques in the fields of power, material, machinery, and transportation, technology is now tending to promote a smaller rather than a larger scale of operations' [Blair (1948, p.151)].

A recent body of literature has emerged documenting a marked shift in the plant-size distribution in manufacturing as suggested by Blair, but taking place a quarter of a century later than he thought. Thus, Carlsson (1989a) showed that the average plant (or establishment) size, measured in terms of employment, declined in 79 of 106 four-digit standard industrial classification (SIC) engineering or metalworking industries in the United States between 1972 and 1982.[1] Similarly, Acs and Audretsch (1990, p. 114) have shown that the small-firm (enterprises with fewer than 500 employees) share of sales in U.S. metalworking industries increased from 30.1% in 1976 to 39.7% in 1986. Declining plant size in manufacturing during the 1970s, reversing the earlier increasing trend, has been reported for several other countries as well [e.g. Storey and Johnson (1990) for the United Kingdom; Loveman and Sengenberger (1991) for the United States, Japan, France, Germany, Italy, and the United Kingdom; and Thurik (1990) for the Netherlands].

Several hypotheses have been proposed to explain this shift. For example, Shepherd (1982) has argued that the adoption of numerically controlled (NC) machine tools may have led to a decrease in the MES, and therefore, plant size, in at least some industries. Similarly, Dodgson (1985) concluded in his comprehensive survey that as market demand becomes increasingly splintered, causing a proliferation in product types, the ability to target production towards specialized product niches is a great advantage. A new tradeoff between flexibility and scale has also been proposed by Piore and Sabel (1984) and Dosi (1988).

In this paper we test the hypothesis that the application of flexible technologies has tended to reduce plant size. In section 2 we set out and explain the hypothesis and its historical background. In section 3 we present an empirical model explaining the change in the average size of establishments. After presenting the empirical results in section 4, a summary and conclusion are provided in the final section. We find evidence consistent with the hypothesis that the application of certain flexible technologies, such as NC machine tools, accompanied by appropriate changes in operating procedures, has contributed to a reduction in plant size.

[1] The metalworking (engineering) industries include non-electrical machinery, electrical machinery, transportation equipment, and instruments.

2. The effect of flexible technologies on plant size

From the Industrial Revolution until the early 1970s, the technology generally applied throughout the metalworking industries promoted mass production: the application of highly mechanized, dedicated (special purpose) machines led to substantial reductions in the cost of producing standardized products. But with the advent of numerically controlled (NC) machines in the late 1940s, the possibility emerged of eventually reversing this technological trajectory favoring large-scale production [Carlsson (1984)]. At first, NC machines were extremely costly and used primarily to enhance human labor in manufacturing complex parts requiring a high degree of precision, particularly in the defense industries. Their initial high cost and limited reliability and programmability (they were hard-wired or punch-card operated) prevented their widespread diffusion for at least a couple of decades [Romeo (1975), Nabseth and Ray (1974), and Carlsson (1990)].[2] Thus, even as late as the end of the 1960s, NC machine tools accounted for no more than one-fifth of U.S. investment in machine tools. In fact, this share declined in the early 1970s and did not exceed 20% until the end of the decade.

The extensive diffusion of NC machine tools did not begin until 1975, when some Japanese producers began to apply microcomputers as the basis for the numerical control unit, thus bringing computer numerical control (CNC) into existence.[3] Suddenly, numerically controlled machine tools became much more easily programmable and therefore more flexible. This gave rise to entirely new applications, extending the potential market to small and medium firms which typically use batch processing in which the benefits of flexibility are much greater than in mass production. This market expansion, in turn, led to sharp price reductions, causing the market to grow further.[4] By 1984, NC/CNC machine tools accounted for 40.1% of all U.S. machine tool investment [Edquist and Jacobsson (1988, p. 25)]. As Carlsson and Taymaz (1994) show, small plants responded much more strongly to the price decline than did large plants; the number of NC machine tools in U.S.

[2] Dodgson (1985) found that the mean cost of a NC machine tool was roughly $140,000, which represented 4.1% of the mean firm sales and 21.8% of the average net book value of plant and machinery in a 1982 sample of 40 engineering firms in Southeast England. See also Burnes (1988).

[3] It is noteworthy that microcomputers were applied in machine tools several years before they were used in personal computers [Jacobsson (1986, p. 9)].

[4] During the period 1983–89, labor costs in manufacturing rose by 26%, while the cost of the most important NC machine tools (lathes and machining centers) *fell* by 22% and 4%, respectively. At the same time, the price of all machine tools rose by 47%. See Carlsson and Taymaz (1993).

engineering industries more than trebled in small plants (with less than 100 employees) between 1983 and 1989, while it grew by a more modest 40% in larger plants.

As a result of this technology shift, the cost of small-scale production has been reduced relative to large-scale production. While large-scale operations may also benefit from the reduced cost of CNC machine tools, they no longer have exclusive access to the technology. Flexibility has increased in large plants, but the inherent flexibility of smaller plants has been enhanced even more, and their productivity has been improved as well, with machines now being affordable which were previously beyond reach.

3. The model

Based on the preceding discussion, our hypothesis is that the application of flexible technology has contributed to a reduction in plant size. In building a model to test this hypothesis, two difficulties must be dealt with. The first is how to measure flexible technology. As indicated above, there are several dimensions of flexibility; no simple measure would be satisfactory. Secondly, changes in plant size are determined not only by the characteristics of technology but also by other factors such as the rate of growth of demand, the rate of productivity growth, and changes in the degree of vertical integration. These variables must also be taken into account.

3.1. Representation of flexible technology

Carlsson (1989b) explains how CNC machine tools enhance three different types of flexibility—operational, tactical, and strategic.[5] Operational flexibility enables a firm to vary its sequencing and scheduling according to need. Tactical flexibility allows fine-tuning in a firm's product mix, rate of production, and modifications of design. Strategic flexibility determines the ability of a firm to anticipate long-term changes in the product and the competitive environment. The programmability of CNC machine tools can play a direct role in increasing the firm's operational and tactical flexibility, while it may play a more indirect and less prominent role in enhancing strategic flexibility. But the flexibility of the machine tools is of no value unless it is accompanied by appropriate changes in procedures, work organization, product design, etc. Thus, for example, it may be necessary to

[5] See also Mills and Schumann (1985).

adjust the production scheduling to take advantage of the programmability of the machine by producing to customer order rather than to inventory. This reduces the optimal batch size as well as the required throughput time (the time required for a part to go through the various steps of the manufacturing process), simultaneously reducing the optimal finished goods inventory.

Therefore, we hypothesize that changes in flexibility are represented by changes in the share of flexible machinery, changes in operating procedures, and changes in internal organization.

ΔNC represents the change in the share of the total number of machine tools accounted for by numerically controlled (NC) machine tools in each industry. It reflects the flexibility of the industry's production machinery. By virtue of their programmability and versatility, NC machine tools provide firms with enhanced ability to accommodate differences among workpieces in terms of size, type, and sequence of operations to be performed, etc. as well as changes or variations in design of the products or parts being processed [Carlsson (1989b)]. Because they are suited particularly well to batch-type production and much less to continuous (mass production) systems, NC machine tools are usually found in plants which make a variety of products in small batches. The more complex the product or part, the greater the likelihood that it is produced with the aid of NC machine tools.[6] Hence, we expect ΔNC to be positively associated with changes in flexibility.

FPI/SHIP represents the change in the ratio between finished product inventory and shipments. The more flexible the production process, the shorter is the required throughput time, and the less time is needed to reproduce the finished goods inventory. Hence, the ratio of finished product inventory to shipments should decline with increasing flexibility.

WIP/INV represents the change in the work-in-process/total inventory ratio. Total inventories consist of raw materials, finished goods, and work-in-process. The smaller the work-in-process inventory (i.e. the fewer are the workpieces that have entered the manufacturing process and are waiting to be further processed), the easier it is to make changes in the scheduling and sequencing of operations, i.e. the greater is the flexibility of the manufacturing process. Conversely, the more complex the production process becomes, the more processing steps are required, and the more capital is tied up in

[6] In addition, Carlsson and Taymaz (1993) found that the number of NC machine tools per employee in U.S. metalworking industries was twice as high in small plants (with less than 100 employees) as in large plants in 1983; as a result of much more rapid diffusion in small plants than in large (measured by employment), the ratio of NC machine tool intensity between small and large plants had risen to 5:1 by 1989.

goods-in-process, the less flexible is the production process.[7] Thus, *WIP/INV* can be viewed as a measure of the change in the complexity of the production process; as such, it is expected to be negatively associated with flexibility.[8]

Summing up, ΔNC, *FPI/SHIP*, and *WIP/INV* represent three different aspects of flexibility, the first being positively and the other two negatively associated with flexibility.

We turn now to the second problem mentioned above, namely that of modeling the relationship between changes in flexibility and changes in plant size. We begin with a discussion of the measurement of plant size.

3.2. Dependent Variables

As has been pointed out in previous literature [Smyth et al. (1975) and Shalit and Sankar (1977)], there is no ideal measure of firm or plant size. The choice of measure depends on the purpose of the study. In comparisons across industries, employment may be the best measure; in other cases total sales, value added, assets, stockholders' equity, or market value may be more appropriate. Even though the measures are often highly correlated with each other, they reflect different aspects of firm behavior and may be explained by different phenomena.

Practical considerations of data availability constrain the choice significantly. Given that we are interested here in changes over time, only average employment by establishments in each industry is directly obtainable from the industrial statistics. But we have also developed an alternative to the average employment measure: average value added in constant 1979 prices (i.e. 1984 value added has been deflated by the producer price index for each industry). The two measures are presented in Table 1.

Even though it is certainly possible for the two measures to diverge, it turns out, on the whole, that they did not during the time period studied here. Average plant size was reduced according to both measures in U.S. metalworking industries, and in most other manufacturing industries as well, between 1979 and 1984, the years for which we have technology data. Average plant size in manufacturing as a whole declined by about 18%

[7] This is illustrated by the fact that the industries with the highest work-in-process/total inventory ratio in 1984 were guided missiles and space vehicles (0.885), aircraft and parts (0.745), and communications equipment (0.640), while the tobacco (0.017) and food and kindred products (0.110) industries were at the opposite end of the spectrum.

[8] Other inventory measures were also tried: the change in the ratio between work-in-process inventory and the value of shipments, and the change in the ratio between total inventories (including raw materials and final goods) and shipments. It was found that both of these measures were highly correlated with *WIP/INV*; they are therefore not included in the regressions reported here.

Table 1
Changes (%) in average plant size, 1979–1984

SIC Code	Industry group and industry	Employment	Value added (in 1979 prices)
2	All manufacturing industries	−0.178	−0.118
20	Food and kindred products	−0.091	0.181
21	Tobacco products	0.044	0.311
22	Textile mill products	−0.142	0.006
23	Apparel, other textile products	−0.121	0.041
24	Lumber and wood products	−0.155	−0.005
25	Furniture and fixtures	−0.166	−0.024
26	Paper and allied products	−0.067	0.026
27	Printing and publishing	−0.118	−0.062
28	Chemicals, allied products	−0.126	−0.058
29	Petroleum and coal products	−0.154	−0.672
30	Rubber, misc. plastics products	−0.199	0.014
31	Leather, leather products	−0.211	−0.015
32	Stone, clay, glass products	−0.174	−0.173
33	Primary metal industries	−0.338	−0.291
341	Metal cans, shipping containers	−0.152	−0.184
342	Cutlery, handtools and hardware	−0.260	−0.216
343	Plumbing, heating except electr.	−0.173	−0.068
344	Fabricated struct. metal prods.	−0.240	−0.227
345	Screw maching prod., bolts, etc.	−0.215	−0.090
346	Metal forgings and stampings	−0.230	−0.104
347	Metal services, n.e.c.	−0.086	−0.084
348	Ordnance and accessories, n.e.c.	−0.127	0.063
349	Misc. fabricated metal products	−0.267	−0.215
351	Engines and turbines	−0.384	−0.304
352	Farm and garden machinery	−0.390	−0.375
353	Construction, related machinery	−0.455	−0.483
354	Metalworking machinery	−0.273	−0.300
355	Special industry machinery	−0.221	−0.202
356	General industrial machinery	−0.220	−0.178
357	Office and computing machines	−0.277	−0.094
358	Refrigeration and service mach.	−0.138	0.031
359	Misc. machinery exc. electrical	−0.173	−0.236
361	Electric distributing equipment	−0.222	−0.155
362	Electrical industrial apparatus	−0.282	−0.214
363	Household appliances	−0.121	−0.024
364	Elec. lighting, wiring equipment	−0.098	−0.103
365	Radio, TV receiving equipment	−0.267	0.325
366	Communication equipment	−0.057	0.115
367	Electronic components, access.	−0.111	0.067
369	Misc. elec. equipment, supplies	−0.287	−0.003
371	Motor vehicles and equipment	−0.280	−0.082
372	Aircraft and parts	−0.204	−0.290
373	Ship, boat building, repairing	−0.213	0.071
374	Railroad equipment	−0.556	−0.636
376	Guided missiles, space vehicles	0.235	0.310
379[a]	Transportation equip., n.e.c.	−0.078	0.233
38	Instruments, related products	−0.154	0.044

[a] SIC industry 379 also includes SIC industry 375 (motorcycles, bicycles, and parts).
Sources: See the Appendix.

according to the employment measure, and by 12% according to the value added measure.[9]

3.2. Other explanatory variables

While our main hypothesis is that the implementation of flexible production technology has contributed to a reduction in establishment size, we are not in a position to measure flexibility directly and incorporate it in a structural model. Instead, we estimate a reduced form model in which the components of flexibility (ΔNC, *FPI/SHIP*, and *WIP/INV*) enter directly. It should be noted, however, that these variables carry the opposite sign of those specified above, since flexibility is hypothesized to be negatively related to average plant size.

As indicated already, changes in average plant size may be due not only to changes in flexibility but also to other variables. Thus, even though our primary focus in this paper is on the relationship between flexibility and plant size, it is necessary at least to control for other explanatory variables, such as the rate of productivity growth (*PRDUCTIV*, measured as the growth of value added per employee) and the growth of demand for the output of each industry (*RLGROWTH*, measured as growth of value added). The problem is that both of these variables incorporate elements of one of the dependent variables (*VALUADD*) and *PRDUCTIV* also an element (employment) of the other (*EMPLOY*). This means that *RLGROWTH* can be included as an independent variable only in regressions with *EMPLOY* as the dependent variable. Instead, we run separate regressions with *PRDUCTIV* and *RLGROWTH*, respectively, as dependent variables and our flexibility variables as explanatory variables. The coefficients have the same expected signs as in the main model (i.e. negative for ΔNC and positive for *FPI/SHIP* and *WIP/INV*).[10]

Finally, μ represents stochastic disturbance. Variable definitions and

[9] The average plant employment declined in all but one (tobacco products) of the two-digit industries and in all but one (guided missiles, space vehicles) of the three-digit industries in the metalworking sectors (SIC 34–37). Average plant output also declined in most industries; the simple correlation between the two measures is 0.70 for all of the two- and three-digit industries and 0.76 for the three-digit metalworking industries alone. There are six two-digit industries and seven three-digit metalworking industries with declining average plant employment which had non-declining output.

[10] Other explanatory variables were also considered, namely changes in the degree of vertical integration, in the degree of specialization, and in the extent of scale economies. However, whether due to measurement errors or other difficulties, their coefficients were mostly insignificant. Their inclusion did not materially change the results and are therefore not reported here.

descriptive statistics are summarized in Table 2. Further explanations and data sources are listed in the appendix.

In summary, in order to test our hypotheses we estimate the following (reduced form) empirical model for each of the two main dependent variables representing change in average plant size (as well as *PRDUCTIV* and *RLGROWTH*):

$$\text{change in average plant size} = \beta_0\text{-}\beta_1 \Delta NC + \beta_2 FPI/SHIP + \beta_3 WIP/INV + \mu,$$

where the change in average plant size between 1979 and 1984 is measured

Table 2
Variable definitions, means, and standard deviations

Variable	Definition	Metalworking industries 33 obs. Mean	Std. Dev.	Manufacturing industries 47 obs. Mean	Std. Dev.
EMPLOY	Change in average establishment employment, 1979–1984	−0.21	0.14	−0.19	0.13
VALUADD	Change in average value added per establishment, deflated by producer price index, 1979–1984	−0.11	0.21	−0.09	0.21
ΔNC	Change in the share of numerically controlled machine tools in the total stock of machine tools, 1977–1983	1.45	1.28	N.A.	N.A.
FPI/SHIP	Change in the ratio of finished products to shipments, 1979–1984	0.43	1.13	0.36	0.96
WIP/INV	Change in the share of work-in-process inventories in total inventories (which also include inventories of final goods and raw material) 1979–1984	−0.06	0.11	−0.05	0.10
RLGROWTH	Growth of value added, deflated by producer price index, 1979–1984	−0.01	0.27	−0.01	0.26
PRODUCTIV	Change in value added per employee, 1979–1984	0.51	0.18	0.50	0.24

Note: 'Change' refers to proportional change between the years indicated for each variable.

either by *EMPLOY* (the change in the average number of employees per establishment) or by *VALUADD* (the change in average plant size as measured by value added in 1979 prices).

Two sets of regressions were run for each dependent variable: one with only three-digit metalworking industries (33 observations including SIC 38), and one with all two-digit manufacturing industries plus the three-digit metalworking industries (47 observations in all). The reason for distinguishing between these two sets of industries is that metalworking machine tools such as NC machines are used primarily in the metalworking industries, whereas the other variables apply throughout all manufacturing industries.

4. Empirical results

The regression results are shown in Table 3, where regressions 1–5 refer to metalworking industries and regressions 6–8 refer to all manufacturing industries.[11] All of the coefficients have the expected sign (except for the coefficients for *FPI/SHIP* in regressions 4 and 5), but not all are statistically significant. The coefficients for *WIP/INV* are highly significant throughout, whereas *FPI/SHIP* is significant only with *EMPLOY* as dependent variable. ΔNC has the expected negative sign but is not statistically significant. Given the latter result, it is not surprising that the estimated coefficients for the other variables are about the same whether the regression is run for metalworking industries alone or for all manufacturing industries.

These results can be interpreted as follows. Changes in flexibility are negatively associated with changes in average plant size. Work-in-process inventories and finished product inventories tend to increase faster in large plants than in small. The share of NC machine tools decreases as plant size increases; more surprisingly, it is also negatively associated with both productivity growth and output growth. However, none of the coefficients for ΔNC is statistically significant —whether because of measurement errors and other statistical problems or because increased use of NC machine tools by itself has little impact. Another possibility is that successful implementation of NC machine tools involves a great deal of learning, the capacity for which varies among firms. It is only when changes in work organization and operating practices are taken into account that increased flexibility affects plant size, productivity, and output growth. It is interesting that increased use of NC machine tools, if it has any impact at all, is negatively associated

[11] Regressions 4 and 5 were also run for all manufacturing industries with very similar results.

Table 3
Regression results for change in average establishment employment (*EMPLOY*) and change in establishment value added (*VALUADD*), 1979–1984

Regr. No.	1	2	3	4	5	6	7	8
Dep. var.	*EMPLOY*	*EMPLOY*	*VALUADD*	*PRDUCTIV*	*RLGROWTH*	*EMPLOY*	*EMPLOY*	*VALUADD*
Constant	−0.1470	0.2073	−0.0494	0.6168	0.1450	−0.1693	−0.1775	−0.0408
	(−3.913)[b]	(3.145)[b]	(−0.733)	(10.516)[b]	(1.566)	(−9.764)[b]	(−11.135)[b]	(−1.298)
ΔNC	−0.0200	−0.0099	−0.0043	−0.0315	−0.0488			
	(−1.184)	(−0.653)	(−0.142)	(−1.195)	(−1.174)			
FPI/SHIP	0.0387	0.0397	0.0130	−0.0124	−0.0005	0.0375	0.0384	0.0109
	(2.354)[b]	(2.756)[b]	(0.439)	(−0.484)	(−0.113)	(2.351)[b]	(2.651)[b]	(0.378)
WIP/INV	0.8842	0.6078	1.0044	0.9129	1.3332	0.7012	0.5000	1.0885
	(4.512)[b]	(3.155)[b]	(2.854)[b]	(2.983)[b]	(2.761)[b]	(4.679)[b]	(3.340)[b]	(4.009)[b]
RLGROWTH		0.2074					0.1892	
		(3.145)[b]					(3.225)[b]	
R^2	0.46	0.60	0.26	0.25	0.21	0.36	0.48	0.27
Adj R^2	0.41	0.55	0.19	0.17	0.13	0.33	0.45	0.24
F-stat	8.40[b]	10.70[b]	3.48[b]	3.24[a]	2.62[a]	12.31[b]	13.42[b]	8.07[b]
No. obs.	33	33	33	33	33	47	47	47

[a] Statistically significant at the 90% level of confidence, one-tailed test
[b] Statistically significant at the 95% level of confidence, one-tailed test
Note: *t*-values in parentheses.

with productivity and output growth. This probably reflects the implementation difficulties just mentioned. Apparently, *FPI/SHIP* has no impact on output and productivity growth, even though increasing finished product inventories are strongly and positively associated with increasing plant size. The only flexibility variable that has a significant impact on productivity and output growth is *WIP/INV*, which tends to be associated with large, complex, and inflexible operations.

5. Conclusion

In this paper we have found that average plant size, as measured by both employment and value added in 1979 prices, declined between 1979 and 1984 in U.S. metalworking (or engineering) industries as well as in U.S. manufacturing industries in general. The decline was quite pervasive, with only a few exceptions.

The overall conclusion from the regression analysis is that we cannot reject the hypothesis that increased flexibility of the production process, as reflected in the adoption of numerically controlled machine tools and changing operating procedures (measured by a reduction of finished product inventories in relation to shipments and a reduction of work-in-process inventories), have contributed to a decrease in plant size, at least if measured in terms of employment. However, the increased flexibility is generally associated with decreased productivity and output growth.

Appendix: Data sources

Data on employment (total as well as production workers only), number of establishments, value added, the value of shipments, vertical integration, and inventories were obtained from U.S. Department of Commerce, Bureau of the Census, *Annual Survey of Manufactures* (USGPO, Washington, DC), for 1979 and 1984.

Data on establishment size (measured by employment) in various size categories were obtained from U.S. Department of Commerce, Bureau of the Census, *County Business Patterns* (USGPO, Washington, DC), for 1979 and 1984.

Data on numerically controlled machine tools were obtained from 'The 12th American Machinist Inventory of Metalworking Equipment, 1976–1978', *American Machinist* (December 1978), and *The 13th American*

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Price data were obtained from U.S. Department of Labor, Bureau of Labor Statistics, *Supplement to Producer and Price Indexes. Data for 1979* (USGPO, Washington, DC, October 1980), and the same for 1984 (USGPO, Washington, DC, October 1985).

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