A list of Working Papers on the last pages

No. 296, 1991

FLEXIBLE AUTOMATION IN THE U.S. ENGINEERING INDUSTRIES

by

Erol Taymaz

March 1991

Forthcoming in the *International Journal of Industrial Organization*

Flexible Automation in the U.S. Engineering Industries

Erol Taymaz
IUI Box 5501
114 85 Stockholm Sweden

(Revised, Nov. 19, 1990)

Abstract: The changes in manufacturing systems and industrial structure brought about by the development of new, computer-based flexible technologies has been a subject of growing debate during the last decade. There is a lack of solid empirical support for almost all hypotheses developed in this debate since data on the relative use of various manufacturing systems are not available for an econometric analysis of the subject. The objective of this paper is to determine the major manufacturing systems and their distribution across the U.S. engineering industries on the basis of machine tool stock data, as interpreted statistically through factor analysis. The results of our analysis show that the use of manufacturing systems based on flexible automation technologies has increased in all of the U.S. engineering industries in late 1970s, partially by replacing mass production systems.

Flexible automation in the U.S. engineering industries(*)

1. Introduction

The changes in manufacturing systems and industrial structure brought about by the development of new, computer-based flexible technologies has been a subject of growing debate during the last decade. There is a lack of solid empirical support for almost all hypotheses developed in this debate since data on the relative use of various manufacturing systems are not available for an econometric analysis of the subject. The objective of this paper is to present a method based on factor analysis to determine the distribution of manufacturing systems across industries, and to construct a data set on the distribution of manufacturing systems based on flexible automation technologies in the U.S engineering industries. The data set is used to analyze the industry characteristics that foster the diffusion of flexible automation in the U.S. The emphasis here is on the relationship between the use of mass production and flexible automation systems. This is the first empirical study of the changes in manufacturing systems at this level of aggregation. Thus, especially given the nature of the method used in this paper, this analysis should be considered as an exploratory data analysis.

The paper is organized in the following way. Section 2 presents a simple analytical framework in which the relationships between various manufacturing systems can be examined. The methodology and results of the factor analysis of

* Previous drafts of this paper have benefitted substantially from many suggestions by Bo Carlsson. I am indebted to Paul A.Geroski, Editor of this *Journal*, and two anonymous referees for very helpful comments.

manufacturing systems in the U.S. engineering industries are presented in Section 3. The determinants of the diffusion of flexible automation systems in the U.S. are examined in Section 4 by using regression analysis. Section 5 concludes the paper.

2. Flexibility and manufacturing systems

Several classifications of metalworking systems have been proposed to date, mostly on the basis of volume/variety characteristics. For our purposes, we could use the usual three-systems classification (piece, batch and mass production systems). Hypothetical cost curves for those systems (PP: piece, BP: batch, MP: mass production) are shown in Figure 1. The most important technological development in manufacturing technologies(1) in recent years is the widespread diffusion of flexible automation technologies after 1975 when the first microprocessor-based numerically control (NC) machine tool produced. Thus, a significant downward shift from BP to BP_{FA} characterizes the effect of this technology in the late 1970s [for a history of machine tool technology, see Carlsson (1984)].

Figure 1 illustrates two important aspects of flexibility. First, the flatter the unit cost curve is, the greater is the flexibility. This dimension of flexibility was first introduced by Stigler and can be named "volume flexibility". Second, the increase in unit cost by increasing the product variety is lower for flexible systems. For example, the difference between BP^L-BP^H curves should be narrower than

1. The focus of this paper is on the engineering industries, i.e. fabricated metal products, non-electrical machinery, electrical machinery, transportation equipment, and precision equipment industries classified in SIC 34-38. Therefore, throughout the paper, "manufacturing systems" refer to metalworking systems used in the engineering industries.

that of MP^L-MP^H curves if the former production type is more flexible. Superscripts ^{L} and ^{H} refer to low and high variety, respectively. "Variety" can be interpreted in many ways such as batch sizes, number of different parts produced, number of design changes, etc., since all of them have similar effects on unit costs. Although a manufacturing system is not necessarily more flexible in both of these dimensions, it is assumed so in this figure. [The concept of flexibility includes other dimensions which cannot be shown in this simple figure. For other dimensions of flexibility, see Carlsson (1989), and Taymaz (1989).]

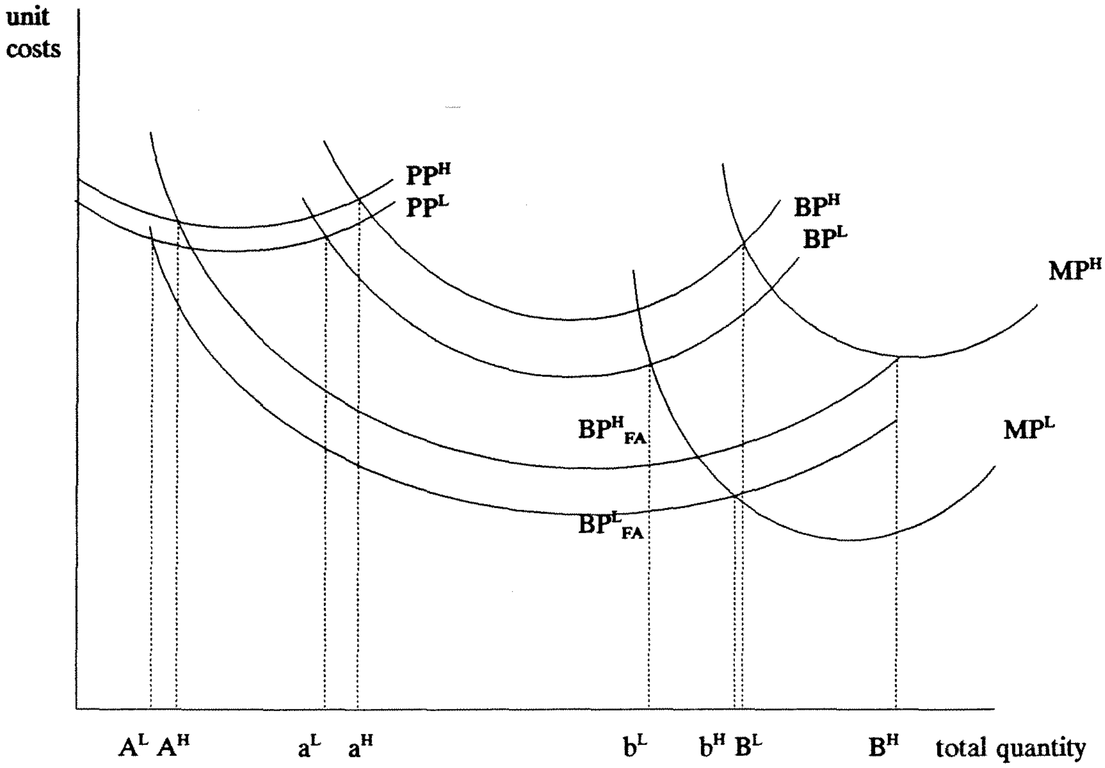
Batch production is more economical than mass production at lower quantities. Moreover, it may be more economical for high-variety production at all levels of output. For example, in Figure 1, flexible automation system (BP_{FA}) can be used even for those quantities higher than B^H for higher variety by duplicating the system instead of using the mass production system since the minimum unit cost of $BP^H{}_{FA}$ is much lower that that of MP^H. In other words, the mass production system is more economical only if total output level is high *and* the variety of production is low.(2)

Batch production systems (and, hence, flexible automation systems) can increase their scope towards the fields previously dominated by mass production under three circumstances. i) Flexible automation technologies may decrease production costs associated with batch production, thereby forcing producers to adopt flexible automation instead of mass production. In other words, a downward

---

2. This type of relation between variety and volume appears in real problems, too. Dietz (1979: 349) reaches the following conclusion in his comparison of NC and automatic lathes: "The result is that almost independently of material the NC machine offers the more favorable solution for total quantities up to 10.000 irrespective of batch size [the low variety case] and up to a batch size of 50 irrespective of the total quantity [the high variety case], while the programme controlled [automatic] machine proves to be economic for greater batch sizes and total quantities".

Figure 1 Cost curves of manufacturing systems



shift from BP^L to BP^L_{FA} will increase the scope of batch production from a^L-b^L to A^L-B^L by improving the cost advantages of this type of production relative to both piece and mass production, as shown in Figure 1. ii) An increase in consumer demand for diversified products may also increase the scope of batch production against the use of mass production systems, because the former type of production presumably has higher variety flexibility. iii) Mass production systems that have lower volume flexibility may be economical no more simply because of the decline in the level of demand and/or increased market instability.

All of these circumstances are important arguments in favor of flexible automation. It is well-documented in the literature that new computerized technologies revolutionized batch production by weakening the link between automation and scale. These technologies have considerably reduced costs of batch production by combining "flexibility" and "automation" in this field [Jacobsson (1986: 9)]. Moreover, intense fluctuations in world markets for engineering goods, growing consumer demand for differentiated products, and intensified international competition after the mid 1970s have emphasized the need for flexibility and flexible automation systems [Cainarca, Colombo and Mariotti (1989)].(3) It sould be added that the current level of these technologies has failed to fulfill the expectations about "volume flexibility", especially in the case of complex, large systems. However, these technologies offer high "variety flexibility" thanks to reductions in time spent for setting-up machines for new jobs. Thus, on the one hand, we find large flexible manufacturing systems (FMSs) working almost 24 hours a day producing small batches to exploit their variety flexibility, and, on the other hand, the use of simple, stand-alone NC machines that allow high degrees of both volume and variety flexibility.

Although major improvements were achieved in the field of batch production in the late 1970s, mass production systems also reduced their unit production costs in the 1980s. First, they also started to reap the benefits of electronics (increasing use of programmable logic controllers, etc.). Second, the improvements in batch production means cheapening of specialized machinery for mass production. For example, in electronics, developments in the design and manufacturing of integrated circuits have led to economical production of "application specific integrated circuits" (ASICs). Third, there is a strong trend

3. There are, of course, counteracting forces in favour of mass production systems. For example, the internationalization of markets brought about by improvements in transportation and telecommunication technologies can give more scope for mass production systems.

towards modularity and standardization of components to boost the production volume in many markets. Piece production systems traditionally based on manual machine controls have also benefitted from new technology. Digital readouts (DROs) are applied largely to conventional machine tools to improve productivity [U.S. Department of Labor (1982: 21)]. The future of the relative use of manufacturing systems depends on complex technological and economic factors. But it is safe to say that controls based on electronics will be adopted to an increasing scale in *all* types of manufacturing systems and even the traditional mass production systems will tend to become more flexible.

It is almost customarily argued in any study on manufacturing technologies that the development of flexible automation technologies has revolutionized the manufacturing processes in the engineering industries starting in the mid 1970s. A sharp downward shift in the cost function of batch production has been achieved by combining "flexibility" and "automation" (the shift from BP to BP_{FA} in Figure 1). Accordingly, these changes in manufacturing technologies have increased the scope for flexible automation systems in the engineering industries, partially by replacing mass production systems. In the following section, this hypothesis will be tested by determining the major types of manufacturing systems and changes in their use in the U.S. engineering industries.

3. Flexible automation in the U.S. engineering industries

The relative use of manufacturing systems can be determined by factor analysis of data on the stock of machine tools since each manufacturing system is a combination of a specific set of machine tools. Although there are many types of manufacturing systems designed for different purposes, factors representing the basic types of manufacturing systems can be found by this method. (Incidentally, the factors found in this analysis roughly correspond to those depicted in Figure 1. The only difference is that there are two separate factors for piece production of small and large workpieces, respectively.)

The database of this analysis is obtained from the 13th American Machinist Inventory of Metalworking Equipment for 43 3-digit industries in SIC 34-38 categories [American Machinist (1983a)]. A summary of the survey's results was published in the American Machinist (1983b). The number of machine tools and related equipment used in metalworking plants in the 48 contiguous United States was estimated in this survey. Data were collected by questionnaire from 12,306 plants during the first half of 1983.

For the factor analysis, 25 groups of metalcutting machine tools are formed by aggregating various types of machine tools because the number of variables (machine types) should be less than the number of observations (industries) for factor analysis. (The original data set contains data about 92 types of metalcutting machine tools.) The aggregation is based on the technological characteristics of machine tools and attempts to form machine groups representing different automation/mechanization levels for each metalcutting operation. This type of aggregation allows us to interpret factors found by our analysis. Thus, 7 of those 25 machine tool groups consist exclusively of NC machines for each metalcutting operation: NC lathes (for turning), NC milling machines, NC drilling machines, NC machining centers, NC grinding machines, NC boring machines, and electro-discharge machines (EDMs). These machines represent flexible automation in our data. Station-type (transfer) machines are the most characteristic for mass production. Non-NC lathes, milling, drilling, boring, and grinding machines are also aggregated into groups based on their mechanization levels (multi-spindle machines, automatic machines, etc.). For example, there are seven types of non-NC milling machines in the original data set. These machines are aggregated into two groups: i) mass-milling (automatic and manufacturing milling machines), and ii) batch-milling (vertical, ram type, general-purpose milling machines, profiling and duplicating, die sinking and engraving and all other non-NC milling machines). The details of aggregation procedure, the codes for each group, and corresponding product codes in production and trade statistics are available from the author upon request.

For each machine tool type, two vintages (0-5 years old, and over 5 years old) are used to get information about the changes in the relative use of manufacturing systems. In other words, there are 86 observations for each machine tool type (2 vintages x 43 industries). Four factors are extracted by using the principal components method, and the oblimin method is used for rotation. The stability of factors with respect to the extraction and rotation methods was checked by comparing the (rotated) factors found by principal axes and maximum likelihood extraction methods, and quartimax and varimax rotation methods. It is found that all procedures lead to almost identical interpretations. (The detailed results of the factor analysis are available from the author upon request.)

The first factor is significantly positively correlated with transfer machines and some other types of machines that are mainly used for high volume production such as rotational grinding, gear cutting, broaching, boring, and automatic milling machines. This factor (MASS) represents the mass production systems. The second factor is significantly positively correlated with all groups of NC machine tools, and negatively correlated with machines that are mainly used for conventional mid-volume production (turret lathes, drilling and automatic turning machines). Thus, this factor (FLEX) clearly represents the new, computerized flexible automation systems. The third factor is positively correlated with heavy lathes, radial drilling machines, vertical lathes, and some types of grinding machines. This factor (PHVY) is related to the batch production of heavy workpieces. The final factor (PIECE) represents low-volume production. It is positively correlated with batch-type milling machines, small lathes, and surface grinding machines, and is negatively correlated with a number of machines that have different characteristics.

Those factor scores that correspond to the older vintage of machine tools are marked by the suffix "78", and those of the newer vintage by "83". Factor scores are shown in Table A.1 in the Appendix. As may be expected, there is a positive correlation between the old and new vintages. In other words, those industries that have a higher share of mass production systems in 1978 (MASS78) tend to have a higher share of those systems in their investment in the period of 1978-1983 (MASS83). The same is also true for the use of other manufacturing systems.

Table A.1 reveals that only 4 of the 43 industries have increased their use of mass production systems. All other industries have invested less in those systems in 1978-1983 than they did before 1978. At the same time, all industries have invested more in flexible automation systems in the same period. These results show that there is indeed a significant increase in the use of flexible automation systems, and a decrease in the use of mass production systems in the U.S. engineering industries in the late 1970s and early 1980s. In other words, manufacturing systems were becoming more concentrated in the region A-B of Figure 1. This change can also be seen in the use of individual machine tools. For example, *only* NC machine tools increased their share more than 50% in this period. The highest increase is shown in the use of NC lathes and NC machining centers. The increase in their shares is more than 700%. Shares of all other types of machine tools with the exception of station-type machines (20% increase) and bench, floor and snag grinders (10% increase) declined. Vertical and turret lathes (both -70%), mass-milling machines (-60%), boring and gear-cutting machines (both -50%) had the highest decline in their shares.

4. The determinants of the diffusion of flexible automation

Our results support the hypothesis that the patterns of use of manufacturing systems are changing. But, as shown in Table A.1, there are significant inter-industry differences in the rate of diffusion. It is therefore necessary to examine the factors influencing the diffusion of flexible automation systems. This will also allow us to test various hypotheses concerning the characteristics of these technologies.

A regression model is formed to determine those factors that enhance the diffusion of flexible automation systems. The model measures the rate of diffusion of new manufacturing systems brought about by the development of microprocessor-based NC machine tools in the mid 1970s as a function of prevailing conditions in the engineering industries. The dependent variable of the regression model is the "change" in the use of those systems, ΔFLEX (= FLEX83 - FLEX78).[4]

The major factor that affects the diffusion of new flexible automation systems in the engineering industries is the composition of manufacturing systems used prior to the diffusion process. Therefore, the variables representing manufacturing systems (MASS78, FLEX78, PHVY78, nad PIECE78) are used as explanatory variables. To the extent that the flexible automation systems extend their scope against the fields of piece and mass production, a positive coefficient for those variables is expected. In other words, a significantly positive coefficient for those variables may indicate that there is indeed a (relative) downward shift in the cost function of batch production by the introduction of new NC technologies, and, as a result of this shift, the scope of batch production has increased from the range of a-b to A-B (see Figure 1). For example, those plants located in the range of b^L-B^L that were using mass production systems before the new flexible technology would tend to invest in flexible automation systems, if those new systems changed the cost structure for that range. On the other hand, those industries that were initially well-endowed with flexible automation systems may have experienced only a small increase in their flexible automation stock in the late 1970s and early 1980s. Hence we expect a negative coefficient for the FLEX78 variable.

The characteristics of products manufactured in the engineering industries

4. Factor analysis generates factor scores in standardized form, i.e., factor scores have zero mean and unit variance. Therefore the dependent variable, ΔFLEX, can be regarded as relative diffusion rate.

should play an important role in the diffusion of flexible automation systems as explained in Section 2. In our model, we employ two variables to measure the effects of product attributes. DIVER, the (log) number of internationally traded products at the 8-digit SIC level, is a proxy for product diversity. This variable is highly correlated with similar variables such as the number of 4-digit sub-industries within each industry. A positive coefficient for this variable may confirm that flexible automation systems have considerably increased the "variety flexibility". For example, in Figure 1, all plants that previously used mass production systems for high variety manufacturing (MP^H) need to invest in flexible automation systems, whereas only a part of the low-variety mass producers (MP^L) would feel that pressure. The same relation holds for other types of manufacturing systems. WIP, the share of work-in-process inventories in total inventories in 1979, is a proxy for product complexity. The manufacturing of complex products typically requires much larger work-in-process inventories because of the extensive operation requirements. The flexible automation systems are suited particularly well to the manufacturing of complex parts. "The use of NC is positively correlated, *ceteris paribus*, with greater part complexity..." [Adler and Borys (1989: 391)]. For example, the manufacturing of engine blocks is relatively complex and thus suitable for NC machine tools, whereas the manufacturing of bolts and nuts may never warrant the use of those types of machine tools. Moreover, it is argued that one of the most significant advantages of these systems lies in reductions in holding WIP inventories. These systems would be more advantegous to those plants that used to have high level of WIP inventories. Thus, the coefficient of this variable is expected to be positive.

These variables are not the only factors that affect the diffusion of flexible automation systems. There are also a number of industry characteristics that should be taken into account in our model. The following variables are also included in the regression estimates.

TECH is equal to the share of technicians in total employment in 1980. There are debates over the skill requirements of flexible automation technologies. Adler and Borys (1989: 391) state that the use of these systems "may uncover a [skill] upgrading trend as machine shops using NC with higher-skilled workers to capitalize on these product characteristics outperform those shops where less-skilled labor prevents them from achieving such gains." If this argument is correct, i.e., if these technologies can be more advantageous for those with higher-skilled labor, a positive coefficient for the TECH variable is expected.

CAPL, the capital-labor ratio, is defined as the value of depreciable assets per employee in 1979. We expect the CAPL variable to have a positive impact for two reasons. First, the CAPL variable may reflect the extent of the use of machinery in production. The engineering plants that are less dependent on the use of metalworking machinery may not feel the pressures to upgrade their machinery so strongly. For example, the plants that are mainly in the (manual) assembly business are in this category. Second, plants that have high capital-labor ratio may have higher investment capacity and, therefore, may have capabilities to increase rapidly their NC machine stocks. SPEC and COVRG are the specialization and coverage ratios as defined in the Census of Manufactures. SPEC is expected to have a negative coefficient since a higher value of this variable (i.e. products classified in other industries have a lower share in the total output of this industry) may show the suitability of this product for specialized (presumably, mass) production. COVRG is equal to the share of an industry in total production of the products classified in it. This variable should have a positive sign; the higher the value of COVRG is, the lower is the integrability of the industry's products into other industries' manufacturing process.

XSHARE, the ratio of exports to domestic supply, is a proxy for the internationalization of production. The coefficient of this variable is expected to be negative because the internationalization can give more scope to mass production systems. ENTRY is equal to the ratio of net entrants to the total number of plants. If new plants tend to employ new technologies, a positive coefficient for this variable would be expected. There are, finally, two variables to capture the effects of competition in the industry: SCALE (the average size of plants in terms of employment that are larger than industry average) and ESTNUM (the (log) number of plants). Although it is controversial whether less concentrated industries are more conducive to rapid diffusion of new technologies, Romeo (1975, 1977) found in his study of the diffusion of NC machine tools that high competition (measured by the number of firms and the variance of the distribution of firm employment in industry) leads to higher rates of diffusion. Therefore, the coefficients of the ESTNUM and SCALE variables are expected to be positive and negative, respectively.(5)

5. Three variables were also tried in the model: R&D intensity (proxy for the frequency of product changes), the standard deviation of annual output in the period of 1977-1985 (proxy for output fluctuations), and average annual rate of output growth. However none of these variables were significant in any estimation.

The complete model is as follows.[(6)]

[1] $\Delta FLEX = \alpha_0 + \alpha_1 FLEX78 + \alpha_2 MASS78 + \alpha_3 PHVY78 + \alpha_4 PIECE78 + \alpha_5 DIVER + \alpha_6 WIP + \alpha_7 TECH + \alpha_8 CAPL + \alpha_9 SPEC + \alpha_{10} COVRG + \alpha_{11} XSHARE + \alpha_{12} ENTRY + \alpha_{13} SCALE + \alpha_{14} ESTNUM + \epsilon$

The regression results are shown in Table 1. In regression 1, where all the explanatory variables are included, the coefficient of determination, R^2, is 87.80, and all the coefficients have the expected sign. Moreover, all but two of the coefficients are statistically significant at the 5% level.[(7)]

The initial extensive use of mass production systems (MASS78) has a significantly positive impact on the change in the use of flexible automation systems (ΔFLEX), and, incidentally, it is the variable that has the highest t-statistic in that equation. The PIECE78 and PHVY78 variables also have positive coefficients. The coefficient of FLEX78 has a negative sign. This means that those

---

6. Note that this equation can be rewritten as follows.
$FLEX83 = \alpha_0 + (1+\alpha_1)FLEX78 + \ldots + \epsilon$
In this case, the share of investment in flexible automation systems in the period 1978-1983 is defined as a function of initial industry characteristics.
In the estimation of the model one may suspect the problem of heteroscedasticity since the dependent variable is an average for plants that form the "industry". Moreover, the way by which factor scores and the dependent variable are calculated may create this problem. The Breusch-Pagan tests were performed to test the existence of heteroscedasticity. The ESTNUM, DIVER, CFLEX, FLEX78, and combinations of these variables are used in heteroscedasticity tests. The null hypothesis of homoscedasticity is not rejected in all tests. Therefore, it is assumed that heteroscedasticity is not a serious problem.

7. Heteroscedasticity-consistent estimates were also found by using White's method. As may be expected, heteroscedasticity-consistent estimates have higher t-statistics for almost all of the coefficients but the increases in t-statistics are not substantial, and there is no change in the interpretation of regression results. This may be viewed as support for the results of heteroscedasticity tests.

Table 2. The determinants of flexible automation

Independent variables	(1) OLS	(2) OLS	(3) IVE	(4) OLS
FLEX78	-0.79		-1.57	
	(-4.07)**		(-2.39)**	
MASS78	0.54	0.33	0.75	
	(6.67)**	(4.26)**	(3.93)**	
PHVY78	0.23	0.02	0.43	
	(3.14)**	(0.37)	(2.36)**	
PIECE78	0.16	-0.13	0.45	
	(1.61)*	(-1.47)*	(1.74)**	
DIVER	0.13	0.17	0.10	0.17
	(2.20)**	(2.32)**	(1.17)	(1.85)**
WIP	0.43	0.55	0.31	0.74
	(3.65)**	(3.89)**	(1.82)**	(5.18)**
TECH	0.07	0.09	0.06	0.03
	(2.60)**	(2.59)**	(1.53)*	(0.76)
CAPL	0.05	0.05	0.05	0.05
	(5.15)**	(4.30)**	(3.97)**	(3.92)**
SPEC	-0.13	-0.12	-0.13	-0.11
	(-5.20)**	(-3.96)**	(-4.33)**	(-3.00)**
COVRG	0.06	0.05	0.07	0.04
	(3.70)**	(2.49)**	(3.22)**	(1.52)*
XSHARE	-3.30	-2.35	-4.22	-0.56
	(-2.50)**	(-1.46)*	(-2.34)*	(-0.31)
ENTRY	0.02	0.01	0.03	0.01
	(1.88)**	(0.63)	(1.96)**	(0.35)
SCALE	-0.19	-0.33	-0.06	-0.39
	(-1.92)**	(-2.84)**	(-.35)	(-3.19)**
ESTNUM	0.09	0.04	0.14	0.05
	(1.42)*	(0.50)	(1.58)*	(0.52)
Constant	4.50	5.63	3.40	5.72
	(2.69)**	(2.75)**	(1.50)*	(2.27)**
R2	87.80	80.60	81.00	64.30
Adjusted R2	81.71	71.90	71.50	53.15
F-statistics	14.40**	9.27**	8.53**	5.76**
Degrees of freedom	14, 28	13, 29	14, 28	10, 32

Notes: Numbers in parentheses are t-values. ** and * mean statistically significant at the 5% and 10% levels, respectively (one-tailed test). OLS: Ordinary least square estimates, IVE: instrumental variables estimates (instrumental variables: industry dummies at the 2-digit level, and all dependent variables except FLEX78). An outlier industry was excluded in regression 4.

Variables: MASS78, FLEX78, PHVY78, and PIECE78: the use of mass, flexible, piece-heavy, and piece manufacturing systems in 1978, DIVER: log of the number of internationally traded products at the 8-digit SIC level, WIP: the share of work-in-process inventories in total value of inventories, CAPL: the value of depreciable assets per employee, TECH: the share of technicians in industry employment, SPEC: the specialization ratio, COVRG: the coverage ratio, XSHARE: the ratio of export to domestic supply (domestic production plus imports), ENTRY: the share of (net) new plants in total in 1979-1984, SCALE: average size of plants that are larger than average in the industry, ESTNUM: log of the number of plants.

Sources: MASS78, FLEX78, PHVY78, and PIECE78: the results of factor analysis of *American Machinist*'s machine tool stock data (see Table A.1). TECH: NSF, *Scientists, Engineers, and Technicians in Manufacturing and Nonmanufacturing Industries: 1980-1981* (Washington, DC: NSF, 1983). SCALE: Bureau of the Census, *County Business Patterns, 1979*. SPEC and COVRG: Bureau of the Census, *Census of Manufacturing Industries, 1977*. DIVER: Department of Commerce, *U.S. Exports* (FT610) and *U.S. Imports* (FT610), 1979. XSHARE: Department of Commerce, *U.S. Commodity Exports and Imports as Related to Output*. All other variables: Bureau of the Census, *Annual Survey of Manufactures, 1979*.

industries that were relatively well endowed with flexible automation systems have lower new investments in those systems. In brief, the regression results support the hypothesis that the flexible automation systems have been replacing other systems, especially mass production systems, in the engineering industries after the mid 1970s.

The product diversity and complexity variables (DIVER and WIP) have also significant positive coefficients in almost all equations. This result supports the hypothesis on the flexibility-enhancing characteristics of new manufacturing technologies. WIP, CAPL, SPEC, and COVRG also have statistically significant coefficients in all equations. Other variables (TECH, DIVER, XSHARE, ENTRY, SCALE, and ESTNUM) have significant coefficients in regression 1.

Because of the way the dependent variable is constructed, the FLEX78 variable can be (contemporaneously) correlated with the error term causing an estimation problem similar to the case of lagged dependent variable - autocorrelation models. In that case the ordinary least squares (OLS) estimates may not be consistent. When the FLEX78 variable was excluded from the model in regression 2, only the coefficient of the PIECE78 variable changed its sign. The ENTRY and ESTNUM variables are not significantly different from zero although they are still positive. There are significant downward biases in these three variables. These results may indicate that the FLEX78 variable is a relevant variable for the model. Therefore, the model is reestimated by using the method of instrumental variables to correct the problem that can be caused by possible contemporaneous correlation between FLEX78 and the error term. The instrumental variables used in this regression are industry dummies at the 2-digit

SIC level, and all other explanatory variables other than the FLEX78 variable (see regression 3). A comparison of those result with the OLS estimates shows that all variables have the same signs and generally high t-statistics.

In regression 4, manufacturing systems variables were excluded from the model to check the sensitivity of the estimates of other variables. In this regression, too, all variables have the expected signs. The TECH, XSHARE, ENTRY, and ESTNUM variables are not statistically significant, presumably because of the significant downward biases in their estimation caused by the omission of relevant (manufacturing systems) variables. However, even in this case, the data still explain 64% of the variation in the dependent variable. The product diversity and complexity, capital intensity, specialization, coverage, and scale variables have coefficients significantly different from zero.

In brief, our results confirm that there is an increase in the use of flexible automation systems, partially by the replacement of mass production systems, in the U.S. engineering industries in the late 1970s and early 1980s. Other factors that enhance the diffusion of these systems are product variety and complexity, capital intensity, coverage ratio, and new entry. The diffusion is lower in those industries characterized by high specialization, high internationalization, and low competition.

Two major limitations of this analysis should be emphasized before concluding the paper. First, our results are limited to the period under investigation, namely the late 1970s and early 1980s. The model may not be valid for later years because new manufacturing technologies may have different characteristics than those developed in the late 1970s. Therefore, for example, the increasing use of electronic control equipment in mass production systems in 1980s may decrease the relative advantages of flexible automation systems in the manufacturing of diversified products. This change may pull the coefficient of the DIVER variable towards zero. Second, our model, and any single-equation model in this manner, cannot usually take into account bidirectional causality relations. For example, competitive pressures in an industry may influence the diffusion of new manufacturing technologies which, in turn, have significant impact on industrial structure. Dynamic simultaneous equation models should be developed for this purpose. The new *American Machinist* survey of metalworking equipment completed at the end of 1989 can supply comparable machine tool data necessary for this purpose.

5. Conclusions

The results of this study confirm the commonly held notion that there was an increase in the use of flexible automation systems, partially by the replacement of mass production systems, in the U.S. engineering industries in the late 1970s. This trend can be reversed only if i) a shift in the focus of technological development occurs in favor of mass production technologies, or ii) high growth rates and stability of markets that can stimulate the use of mass production systems can be achieved in the engineering industries. Both of these developments seem highly unlikely in the near future. Hence, the shift towards the use of flexible automation systems away from mass production can be expected to continue in the medium-run even though mass production systems are being made more flexible by the off-springs of new technologies.

References

Adler, P.S. and Borys, B., 1989, Automation and Skill: Three Generations of Research on the NC Case, **Politics and Society** 17, 377-402.

AM, 1983a, **13th American Machinist Inventory of Metalworking Equipment: Market Potentials Report.**

AM, 1983b, 13th American Machinist Inventory of Metalworking Equipment 1983, **American Machinist** 127, no.12, pp.113-144.

Cainarca, G.C., Colombo, M.G., and Mariotti, S., 1989, An Evolutionary Pattern of Innovation Diffusion. The Case of Flexible Automation, **Research Policy** 18, 59-86.

Carlsson, B., 1989, Flexibility and the Theory of the Firm, **International Journal of Industrial Organization** 7, 179-203.

Carlsson, B., 1984, The Development and Use of Machine Tools in Historical Perspective, **Journal of Economic Behavior and Organization** 5, 91-114.

Dietz, P., 1979, Is the NC Lathe the Most Economic Solution in Every Case?, in: B.J.Davies, ed., **Proceedings of the Nineteenth International Machine Tool Design and Research Conference** (held in Manchester, 13th-15th September 1978, London: The MacMillan Press Ltd.) 341-351.

Jacobsson, S., 1986, **Electronics and Industrial Policy: The Case of Computer Controlled Lathes** (London: Allen&Unwin).

Romer, A.A., 1977, The Rate of Imitation of a Capital-embodied Process Innovation, **Economica** 44, 63-69.

Romer, A.A., 1975, Interindustry and Interfirm Differences in the Rate of Diffusion of an Innovation, **Review of Economics and Statistics** 57, 311-319.

Shrieves, R.E., 1978, Market Structure and Innovation: A New Perspective, **Journal of Industrial Economics** 26, 329-347.

Taymaz, E., 1989, Types of Flexibility in a Single-machine Production System, **International Journal of Production Research** 27, 1891-1899.

US Department of Labor, 1982, **Technology and Labor in Four Industries** (Washington, D.C.: GPO).

APPENDIX

Table A.1. Factor scores representing manufacturing systems

SIC Code	INDUSTRY	ΔFLEX	ΔMASS	ΔPHVY	ΔPIECE	FLEX78	MASS78	PHVY78	PIECE78
376	Guided missiles and space veh.	3.70	-0.47	-0.89	-0.10	-0.76	1.30	-0.24	0.53
379A	Misc. transportation	3.08	-2.37	-0.72	-0.89	-0.01	4.08	0.12	-0.19
354A	Machine tools	2.66	-0.93	-0.84	-0.40	-0.08	1.33	1.16	1.15
386	Photographic eqmt and supplies	2.43	-0.13	0.24	0.08	-0.73	-0.22	-0.17	1.31
353A	Construction, mining eqmt	2.04	-0.93	-2.03	-0.89	-0.11	0.73	3.23	-0.38
372B	Aircraft engines and parts	1.99	-1.40	-1.29	-1.08	0.06	1.30	1.28	1.06
356	General inds. mach. and eqmt	1.91	-0.75	-0.85	-0.38	-0.75	1.64	0.83	0.23
351	Engine and turbines	1.88	0.22	-1.57	-0.29	-0.50	1.47	0.89	-0.41
367	Electronic components and acc.	1.85	-0.59	0.41	-0.70	-0.54	-0.01	-0.71	1.46
366	Communications eqmt	1.84	-0.67	0.21	-0.60	-0.75	-0.06	-0.42	1.07
357	Office,comp. and account. machines	1.83	-0.73	-0.44	-0.09	-0.67	0.10	-0.49	0.78
359	Misc. machinery, except electrical	1.76	-1.08	-0.53	-0.70	-0.33	1.05	0.78	1.15
349	Misc. fabricated metal products	1.76	-0.50	-0.68	-0.69	-1.05	-0.07	0.44	0.06
358	Refrigeration and serv. ind. eqmt	1.64	-1.77	-0.25	-1.10	-1.27	0.26	0.10	-0.50
369	Misc. elec. mach. and eqmt	1.63	-0.97	-0.16	-0.11	-1.16	0.60	-1.18	0.42
381	Engrg,lab,scientific eqmt	1.49	-1.37	-0.75	-0.78	-0.95	0.41	-0.39	1.21
355	Special industrial machinery	1.43	-0.94	-1.20	-0.67	-0.35	0.37	1.85	0.83
363	Household appliances	1.42	-0.58	-0.11	-0.56	-0.82	0.01	-0.51	0.47
352	Farm and garden machinery and eqmt	1.35	-1.11	-0.19	-1.19	-1.44	0.43	0.14	-0.83
374	Railroad eqmt	1.33	-1.46	-1.40	-1.05	-0.93	0.86	1.14	-0.86
362	Electrical industrial apparatus	1.33	-0.89	-1.08	-0.41	-0.86	0.54	0.30	0.36
382	Measuring and controlling instr.	1.25	-0.06	-0.31	-0.11	-1.27	-0.01	-0.78	0.52
384	Surgical, medical and dental instr.	1.24	0.14	-0.04	0.43	-1.29	-0.30	-0.58	0.57
354B	Other mtwrkng mach.,eqmt and acc.	1.21	-1.40	0.14	-0.79	0.15	1.01	0.65	1.86
341	Metal cans and shipping con.	1.19	-0.51	-0.04	-2.01	-0.56	-0.50	1.12	1.31
343	Heating eqmt and plump. fixtures	1.00	-1.11	-0.16	-0.79	-1.67	-0.54	0.04	-0.34
344	Fabricated str. metal products	0.99	-0.61	-0.47	-0.87	-0.46	-1.12	1.47	-0.60
371B	Motor vehicle parts and acc.	0.98	0.18	0.06	-0.30	-0.75	2.28	-0.97	-1.21
348	Ordnance and accessories	0.91	0.08	-1.25	-3.88	-0.16	0.78	-0.44	1.71
361	Elec. trans. and distr. eqmt	0.91	-0.10	-0.77	-0.13	-1.10	-0.49	-0.08	0.41
364	Elec. lighting and wiring eqmt	0.89	-0.14	0.26	0.26	-1.04	-0.52	-0.98	0.00
345	Screw machine products	0.85	-0.02	0.07	-0.30	-1.34	0.80	-1.96	-0.32
346A	Metal forgings	0.84	-0.94	-1.28	-0.52	-0.41	0.06	2.28	0.35
383A	Optical instr., ophthalmic goods	0.82	-0.89	-0.18	-1.76	0.02	0.47	-0.06	1.99
372A	Complete aircraft	0.80	-1.04	-0.92	-0.93	-0.50	-0.37	0.49	-0.25
353B	Materials handling mach. and eqmt	0.77	-1.14	-1.53	-1.91	-0.87	-0.28	1.90	-0.35
342	Cutlery, hand tools & gen.hardware	0.68	-0.49	-0.54	-0.43	-1.14	0.05	-0.75	-0.22
346B	Metal stampings	0.62	-0.16	0.02	-0.03	-0.44	-0.48	0.42	0.79
387	Watches,clockwork operated devices	0.57	-1.46	1.20	-1.28	-1.26	-0.16	-1.59	0.46
371A	Complete motor vehicles	0.50	-0.30	-0.07	-0.68	-0.64	0.05	-0.36	-1.71
373	Ship and boat building and repair.	0.46	-1.31	-1.55	-0.51	-0.32	-0.88	3.05	-0.43
365	Radio and TV eqmt	0.31	-1.45	0.33	-2.76	-0.88	-0.13	-1.00	1.17
347	Coating, engraving and other ser.	0.13	-1.81	0.11	-0.15	0.79	1.13	0.51	1.38

Note: Ranked by ΔFLEX.