Patterns of Advanced Technology Adoption and Manufacturing Performance*:*

Employment Growth, Labor Productivity, and Employee Earnings

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ABSTRACT

Previous studies of the relationship between technology adoption and performance in U.S. manufacturing plants take the number of technologies in use as a measure of technological sophistication. These studies generally find a positive monotonic relationship between technology counts and employment growth and earnings and productivity levels among otherwise similar plants. However, the technology count approach masks potential differences in performance among plants that adopt the same number, but different combinations, of technologies. The present study advances earlier work by examining how plant performance is associated with specific technology combinations.

The analysis yields several important insights. First, there is enormous diversity in technology adoption patterns. Second, specific technology combinations (*e.g.*, computer aided design combined with numerically controlled machines *vs.* computer aided manufacturing combined with numerically controlled machines) generally have different degrees of association with plant performance, even among the plants that adopt the same number of technologies. Third, plants that integrate fabrication with assembly operations appear to use advanced technologies more effectively than those engaged in only fabrication or assembly.

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I. INTRODUCTION

Since the mid-1950s, empirical studies of aggregate economic performance have generally attributed the portion of output growth that cannot be explained by increases in labor and capital to technological progress. Alternatively, some researchers augment the output growth models by using aggregate R&D expenditures or the number of scientists and engineers as proxies for the level of technology.[1] Measurements of technology's direct contribution to job creation, productivity, and earnings growth at the manufacturing plant level have been based on anecdotal evidence or on relatively small-sample surveys of firms or plants. Recently, however, a large data set collected in the 1988 Survey of Manufacturing Technology (SMT) has provided important information on the extent to which specific technologies were used in manufacturing plants. These data have been used, notably by researchers affiliated with the Center for Economic Studies (CES) at the U.S. Bureau of the Census, to analyze relationships between technology use and a number of plant performance measures or attributes.[2]

In the 1988 SMT, plant managers were asked which of 17 advanced technologies they had adopted as of the survey year. Several recent studies have used this valuable information. A common feature of these studies is the use of counts of technologies adopted by a plant as the measure of technology sophistication, *i.e.*, the numbers of surveyed technologies used in the plants. This approach ignores the possibility that the way technologies are combined, and not just the number of technologies, may be important in affecting plant performance.

In this paper, we examine how specific technology combinations are statistically associated with job creation, productivity, and earnings. We demonstrate that using data on detailed technology adoption patterns yields a richer picture of the relationships between technology adoption and plant performance than using technology counts. Specifically, we demonstrate there is enormous diversity in the technology adoption patterns, even within the same industry group or type of operations (that is, fabrication, assembly, or both).[3] Second, we show there are important

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[1] This research is summarized in U.S. Bureau of Labor Statistics (1989). The classic explanation of the role of technical knowledge as a "residual" factor in the growth process is Solow's (1957). Fagerberg (1994) reviews this literature within the context of international differences in growth rates.

[2] For a review of this literature, see Alexander (1994).

[3] Discrete manufacturing, the primary type of production in the 1988 SMT that is used in industries examined in this report, involves six basic steps (U.S. Congress 1984, pp. 39-41) including: (1) materials handling (the conveyance of raw materials and work-in-process from storage to processing and/or assembly stations); (2) fabrication (the casting, extrusion, or forging of metal, plastic, and/or ceramic parts); (3) machining (the removal of material or stamping/bending of sheet materials to produce a desired shape); (4)

differences in the degrees of association between technology combinations and plant performance across technology combinations that include equal numbers but different types of technologies. Third, we show that plants that integrate fabrication with assembly may use advanced technologies more effectively than those engaged in either fabrication or assembly alone.

In Section II, we describe the data set used in this study and review some related literature. In Section III, we summarize the most commonly adopted technology combinations. In Section IV, we present the methods used to analyze the relationships between technology combinations and plant performance as well as our principal findings. Finally, in Section V we summarize our main findings and present some concluding remarks.

II. DATA AND RELATED LITERATURE

The data sources for this study are the Longitudinal Research Database (LRD), compiled from the Censuses of Manufactures and Annual Surveys of Manufactures, and the 1988 Survey of Manufacturing Technology (SMT).

The 1988 SMT surveyed a stratified sample of 10,526 (out of a universe of 39,556) U.S. manufacturing establishments with more than 20 employees. The plants were in the following industries: fabricated metal products (Standard Industrial Classification code 34), industrial and commercial machinery and computer equipment (SIC 35), electronic and other electric equipment and components except computer equipment (SIC 36), transportation equipment (SIC 37), and instruments and related products (SIC 38). The U.S. Bureau of the Census conducted the survey from September through November 1988 to determine the breadth of adoption of 17

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finishing (removing "burrs" from machined parts and/or washing, polishing, or coating the parts); (5) assembly; and (6) quality control. However, the SMT classified plants into four types: fabrication and/or machining, assembly, both fabrication and assembly, and neither fabrication nor assembly (which includes only a small number of plants). (In the present report, "fabrication" refers to fabrication and/or machining to simplify our exposition.)

In contrast, in continuous process industries (for example, food, paper and pulp, chemicals, petroleum refining, and metallurgy), materials flow continuously through the production process, are blended or react with other materials, and are heated, cooled, distilled, dried, etc. In the 1950s and 1960s, continuous process industries pioneered the use of computers to continuously regulate production processes (Bedworth, et al., p. 354-357). As a result, the nature of work changed from direct physical participation in the production process to monitoring the production process via computer terminals. As the cost of microprocessors plummeted beginning in the 1960s, discrete manufacturers began to adopt advanced computerized technologies in an effort to emulate the levels of control and optimization achieved in the continuous process industries. As the features of discrete manufacturing become less distinct from those of continuous process manufacturing, the question arises: will workers in discrete industries face similar changes in the nature of their work (Zuboff 1989, pp. 418-422)?

advanced technologies.[4] (Appendix C defines and briefly describes these technologies.) In addition, the survey asked questions on plans to adopt advanced technologies, average product prices, type of operations (assembly, fabrication, both, or neither), plant age, and type of market served. The survey did not ask when the plants adopted the technologies or how intensively the plants used the technologies.

Researchers at CES matched the 1988 SMT data to corresponding plant data contained in the LRD.[5] These data constitute the basis, in the present study, for analysis of 1987 earnings and productivity levels. When studying the rates of job and earnings growth, we include only plants with employment data for both the 1982 and 1987 Censuses of Manufactures.[6]

CES researchers used the same data set in earlier studies of advanced technologies and plant performance, *e.g.*, Dunne and Schmitz (1995). In addition, Doms, Dunne, and Roberts (1994) supplement these data with data from the 1991 Standard Statistical Establishment List (SSEL). Doms, Dunne, and Troske (1994) add data from the Worker-Employer Characteristics Database (WECD). The WECD matches employee data from the 1990 Census of Population to establishment-level data (from the 1987 Census of Manufactures) on their presumed workplaces. Since these studies are closely related to the present study, we briefly review them below.[7]

Doms, Dunne, and Roberts (1994) find that plants that adopted more of the SMT technologies experienced higher rates of employment growth and lower closure rates than otherwise similar plants using fewer technologies. The analysis controls for variables that may be associated with advanced technology adoption, such as productivity and capital-labor ratio.[8]

Dunne and Schmitz (1995) find that the "most technology intensive" plants (*i.e.*, those plants that used six or more of the 17 SMT technologies) paid wage premia of about 16 percent to their production workers and 8 percent to their non-production workers, compared with otherwise similar plants. Their regression analysis suggests that the technologies explain up to 60 percent

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[4] U.S. Bureau of the Census (1993 and 1995) describes two subsequent surveys of manufacturing technology. In addition, a recent study based on the 1988 and 1993 SMT data is McGuckin, Streitwieser, and Doms (1995).

[5] After dropping the plants in the 1987 Census of Manufactures whose data were imputed by the Bureau of the Census rather than reported by plant managers, a matched data set of 6,968 plants remained (Dunne and Schmitz, 1995, pp. 9-12).

[6] Since we do not know which records in the 1982 Census were imputed, we do not exclude plants whose 1987 records were imputed in our study of growth rates. Plants established after 1982 and plants that exited before 1987 could have very different degrees of association between technology adoption and plant performance, and warrant a separate study.

[7] After this study was substantially completed, two studies of the relationships between technology use and plant performance appeared in draft form. They are McGuckin, Streitwieser, and Doms (1995) for the U.S. and Baldwin, Diverty and Johnson (1995) for Canada. Both studies explore alterative ways to measure technology, but do not attempt to examine the impacts of specific technology combinations on plant performance.

[8] Doms, Dunne, and Roberts estimated the equations of employment growth and plant closure rates simultaneously. Like most other related studies, the present study uses a single-equation approach.

of the estimated wage premium paid by large plants. They also find that the most technology intensive plants employed relatively more non-production workers than otherwise similar plants.

There is some evidence suggesting that the technologies are complements to human capital but still have a positive association with wages. In particular, Doms, Dunne, and Troske (1994) find that including data on workers' education and occupation in regressions similar to those estimated by Dunne and Schmitz diminished but did not eliminate the positive and statistically significant association between technology adoption and wages. Their study also analyzes the association between advanced technology adoption and skilled-worker employment shares.

III. PATTERNS OF TECHNOLOGY ADOPTION

The report on the 1988 SMT published by the Bureau of the Census contains a wealth of statistics about the frequency of adoption of each of the 17 technologies (U.S. Bureau of the Census 1989). However, it does not report the frequency of adoption of specific combinations of technologies. There is a great deal of variation in the combinations of technologies adopted by manufacturing plants, even within the same two-digit major industry group or within a given type of plant operation (*e.g.*, assembly, fabrication, or both).

Table 1 shows the diversity of the technology combinations for all plants and for three subgroups of plants with different types of operation.[9] Several conclusions emerge from this table. First, there is an enormous diversity in technology adoption patterns among plants. Only 13 specific combinations were used by more than 70 sampled plants (out of a total of 10,526 sampled plants). The plants using these most frequently used technology combinations together account for less than 20 percent of all sampled plants.[10] A large proportion of plants report technology combinations adopted by fewer than 2 sampled plants.[11]

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[9] Based on the entire SMT sample, a chi-square test of goodness-of-fit provides strong evidence that technology combinations are not independently and randomly adopted by plants from the 17 SMT technologies.

[10] The plants that used one to eight technologies account for more than two-thirds of all plants in the sample.

[11] About 27 percent of the plants that adopted between one and eight technologies (or 18 percent of all sampled plants) adopted technology combinations that were found only in one or two plants.

Table 1: Most Frequently Adopted Technology Combinations, Overall and by Process

Technologies	All Plants		Fabrication		Assembly		Fabrication and Assembly	
	%	Rank	%	Rank	%	Rank	%	Rank
Computer aided design (CAD)	6.5	1	3.9	2	12.3	1	5.3	2
Numerically controlled tools (NC)	6.0	2	11.2	1	1.2	7	6.8	1
CAD+NC	2.8	3	2.0	5	0.7	9	3.9	3
Programmable logic controllers (PLC)	2.2	4	3.0	3	1.6	5	1.8	4
Computers used for control on plant floor (CC)	1.5	5	1.6	8	2.4	2	1.2	10
CAD+NC+CAD output used to control machines	1.5	6	2.0	5	0.4	12	1.7	6
NC+PLC	1.4	7	2.4	4	0.6	10	1.6	7
CAD+NC+PLC+CC	1.4	8	1.6	8	(D)	(D)	1.8	5
WAN connections to customers and/or suppliers	1.3	9	1.4	9	2.4	2	1.0	14
PLC+CC	1.2	10	1.0	11	1.6	4	0.9	15
CAD+NC+PLC	1.1	11	1.1	10	(D)	(D)	1.5	8
CAD+PLC	1.1	12	0.5	14	1.9	3	1.0	13
NC+PLC+CC	1.1	13	1.8	6	(D)	(D)	1.3	9
Total	29.1		33.5		25.1		29.8	

% = percent of plants with between 1 and 8 technologies within each category. (D) = suppressed for disclosure purposes. Totals do not include combinations with (D).

Computer Aided Design (CAD; see technology 1 in Appendix C for detailed definitions) and Numerically Controlled (or computer numerically controlled) tools (NC; technology 5) used as stand-alone technologies are the two most widely used technology combinations in the sample; stand-alone adoption of Programmable Logic Controllers (PLC; technology 16) and Computers used for Control on the factory floor (CC; technology 17) were the fourth and fifth most widely used combinations. Plants also frequently adopted various combinations of these four technologies. The combination of NC and PLC and/or CC may indicate a conversion of older NC equipment that was originally programmed using punched tapes to the more sophisticated and flexible Computer Numerically Controlled tools (CNC) (Bedworth, et al. 1991, pp. 457-461). The use of CAD output to control machines (also known as computer aided manufacturing or CAD/CAM; technology 2), combined with CAD and NC may facilitate the integration of part design and fabrication and reduce programming time. The use of Wide Area Network (WAN; technology 15) connections with suppliers and/or customers may speed design and delivery and reduce inventories.

Second, the pattern of combination in some cases suggests a “natural” progression or technology “ladder” that plants follow when they expand their acquisition of technologies. Among the more frequently used simple and complex technology combinations, the simple combinations are often subsets of more complex combinations. The three most frequently adopted pairs of technology combinations—CAD and NC, NC and PLC, and PLC and CC—are composed of four of the five most frequently adopted stand-alone technologies. The most frequently adopted combination of three technologies is CAD, NC, and CAD/CAM. This technology combination includes a combination of one of the most frequently adopted pairs of technologies mentioned above (*i.e.*, CAD and NC) and CAD/CAM technology. The most frequently adopted combination of four technologies is the combination of CAD, NC, PLC, and CC, a combination of two of the frequently adopted pairs of technologies—the pair of CAD and NC, and the pair of PLC and CC.

Third, there are sharp differences in the pattern of technology adoption among plants, depending on their operations. Assembly plants are far more likely than other plants to use CAD alone or in combination with other technologies, especially programmable control and local area networks. Assemblers are also less likely than fabrication plants to adopt NC and more apt than integrated plants to adopt local area networks and networks that link the plant to customers and/or suppliers. In contrast, fabrication plants are much less likely to adopt network technologies, suggesting that assemblers are using network technologies to improve internal coordination of the production process, which may be less urgently needed in fabrication plants. The differences among technology adoption patterns across the five major industry groups (not shown in the table) appear to be somewhat less pronounced than those across production processes.

Fourth, fabrication plants have an adoption pattern broadly similar to that of plants that engage in both fabrication and assembly. Fabrication plants, however appear to be more apt to adopt programmable control as a stand-alone technology and less apt to adopt computer aided design, compared with more integrated plants, which constitute the majority of plants.[12]

IV. ANALYTICAL METHOD AND FINDINGS

The enormous diversity of the technology adoption pattern suggests that associations of technology combinations with measures of plant performance may differ in sign and magnitude across different technology combinations composed of the same number of technologies. Using the number of technologies adopted by a plant as the measure of technological sophistication may obscure such differences. In this section, we show that this is indeed the case. We find that (1) various technology combinations have different associations with plant performance, and (2) the same technology combination could have different associations with plant performance, depending on whether the adopting plant is an assembler, fabricator, or both.

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[12] Plants integrating fabrication and assembly account for 58.1 percent of the plants on a weighted basis; the percentages for the other operations categories are 15.7 for assembly, 19.0 for fabrication, and 7.2 for plants that engage in neither fabrication nor assembly (U.S. Bureau of the Census 1989, p. 7).

We use regression analysis to explore the statistical associations between frequently adopted technology combinations and 1987 levels of earnings and productivity and the rates of growth of employment, earnings, and productivity between 1982 and 1987. This analytical method controls for the potential effects of many other observable plant characteristics.

We estimate regressions for both levels of and changes in earnings and productivity. The earnings and productivity dependent variables in the levels regressions are expressed as logarithms. In this form, the coefficients of the technology variables (which take a value of one or zero) are approximately the percent difference of the dependent variable associated with the adoption of a particular technology or technology combination, when compared with otherwise similar plants that adopted none of the SMT technologies (the reference group).[13] The dependent variables in the growth rate regressions are expressed as the difference in the logarithms of the 1987 and 1982 levels. The coefficient for each technology variable in the growth regressions is the difference in the five-year growth rate of the dependent variable associated with the adoption of a particular technology or technology combination, compared with the reference group.[14]

The technology variables that are the focus of this paper are represented by a set of dummy variables, each identifying whether a specific technology or combination of technologies was adopted by the plant. Specifically, dummy variables are included for the ten most common technology combinations within each technology count class, for one to six technologies. In addition, for each technology count class, a separate dummy variable represents all of the other less frequently adopted technology combinations.[15] Finally, we include a single dummy variable to indicate whether the plant adopted any combination of seven or more technologies. The regressions also control for other plant characteristics, including plant size, age, multi-unit status, capital/labor ratio, region, and four-digit SIC industry. (Appendix B provides a complete list of the dependent and independent variables.) The model specification is similar to that used in Dunne and Schmitz (1995), which facilitates comparisons with their work. Unlike Dunne and Schmitz, we use weighted least squares regression.[16]

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[13] For example, a coefficient of 0.25 for a particular technology variable indicates that adoption of that technology combination is associated with a 25 percent higher value of the dependent variable compared with the dependent variable's value when none of the SMT technologies are adopted.

[14] In this case a coefficient of 0.25 indicates that adoption of the technology is associated with a 25 percentage points higher five-year growth rate of the dependent variable than in the absence of any of the SMT technologies.

[15] For example, we included dummy variables for each of the top ten technology pairs among the plants that adopted exactly two technologies and one additional dummy variable for all other technology pairs. Thus, for each count class (up to six technologies), eleven technology dummy variables are included as explanatory variables in the regression analyses. One could argue that the rarer technology combinations are not representative of typical manufacturing plant technology implementation. Alternatively, one could argue that the rarer technology combinations are more "advanced" than the more commonly observed technology combinations, as may be the case for lasers, robots, and automated materials handling equipment.

[16] The SMT sample weights were used in the weighted least squares regressions. The sample weights are the inverses of the probability of being sampled for individual plants, depending on the employment size/three digit industry strata used to collect the data. A rationale for using the sample weights in weighted least squares regression analysis is that doing so tends to diminish misspecification bias if an interaction term comprising a variable that is correlated with the stratification variable is omitted. The

Analyzing the relationships between technology adoption and plant performance by using the number of technologies adopted by plants as a measure of technology sophistication implicitly assumes that what matters is how many, rather than which, technologies a plant adopts.[17] This assumption is inconsistent with observed data. We tested the hypothesis that the coefficients of all technology variables within each technology count class were equal and rejected the hypothesis at the 99 percent level of confidence. The result underscores the degree to which different technology combinations are differently associated with plant performance.

Table 2 summarizes regression results (fully shown in Appendix Tables A-1 and A-2). The table reports the number of technology coefficients that are positive or negative. and whether they were statistically significant. It provides an impressionistic summary of the extent to which technology combinations are associated with higher or lower employment growth, labor productivity, and employee earnings.

Table 2:
Summary of Regression Results: Number of Technology Associations by Sign and Significance

	1982-1987 Growth Rates				1987 Levels			
	Positive		Negative		Positive		Negative	
	Sig	Total	Sig	Total	Sig	Total	Sig	Total
Total Employment	14	40	1	11				
Production Worker Employment	15	42	2	9				
Non-production Worker Employment	7	37	3	14				
Labor Productivity	8	29	1	22	18	53	1	14
Production Worker Earnings	7	35	3	16	23	53	1	14
Non-production Worker Earnings	4	26	4	25	7	40	10	27

Sig=technology associations significantly different from zero at 95% confidence level. Total number of coefficients in the 1987 panel is not equal to number of coefficients in the 1982-87 panel because 16 non-significant coefficients had to be suppressed to avoid disclosure of confidential data were excluded from the 1982-87 panel. This table is a summary of Tables A-1 and A-2.

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question of whether to use sample weights is an empirical and not an analytical issue and reflects the researcher's confidence in the model specification (Bloom and Idson 1991, p. 620). We applied the test developed by DuMouchel and Duncan (1983) for deciding whether to use weighted least squares and rejected the hypothesis of no misspecification bias in the OLS regressions at the 95 percent level of confidence in nearly all cases. More technology coefficient estimates are statistically significant in the weighted least squares regressions than in the ordinary least squares regressions. Finally, when analyzing technology adoption patterns, we do not drop plants with imputed LRD data from the sample, nor do we weight the observations using the sample survey weights.

[17] An alternative interpretation is that all (or nearly all) plants that adopt n technologies adopt the same combination of n technologies. The evidence indicates that this is not the case, at least when n is small (between 1 and 8). We find that there is considerable heterogeneity in technology adoptions patterns within technology count classes.

EMPLOYMENT GROWTH

Total employment is flat from 1982 to 1987 for the plants that do not adopt any of the 17 SMT technologies. In contrast, total employment growth is positive and statistically significant for many technology combinations. The highest rate of employment growth (27 percent over the five years) is associated with the adoption of local area networks for the exchange of data on the factory floor (technology 14), followed by 23 percent for the adoption of CAD (technology 1) and local area networks for the exchange of data within engineering or design departments (technology 13). The adoption of CAD and CAD output used in procurement (technology 3) is associated with a decline in employment of 19 percent over the period.

Production and non-production worker employment growth rates are related to the adoption of technology combinations differently. Compared with plants that do not adopt any SMT technology, employment growth of production workers ranges from 35 percentage points *higher* for plants that only adopt local area networks on the factory floor (technology 14) to 38 percentage points *lower* for plants that adopt CAD and use CAD output for procurement (technologies 1 and 3). The latter establishments may contract out much of their fabrication of parts or may primarily engage in design, which uses fewer production workers than other establishments. Most of the technology combinations associated with higher production worker employment growth rates include CAD combined with network technologies (technologies 13, 14, or 15) or NC (technology 5).

We find that production and non-production worker employment growth rates do not exhibit a monotonic and positive association with the numbers of technologies. (Doms, Dunne, and Roberts do find such an association for total employment growth.) In particular, plants that adopt seven or more technologies increase production worker employment at a rate 11 percentage points faster than plants that adopt none of the SMT technologies; but many technology combinations with fewer than seven technologies increase production worker employment even faster, *e.g.*, LAN for factory use, the combination of CAD, NC, and PLC with or without computers used for control on the factory floor.

Few technology combinations have statistically significant associations with non-production worker employment growth, and more of the relationships are negative than for production workers. Some technology combinations are associated with non-production worker employment growth that is 9 to 36 percentage points higher than the reference group. These combinations generally consist of programming-intensive technologies such as CAD and/or NC and technologies that facilitate the exchange of data within the firm and with suppliers (CAD output used to control machines, CAD output used in procurement, and local area networks). Flexible manufacturing cells are associated with the slowest non-production worker employment growth, as much as 73 percentage points *lower* than similar plants adopting no SMT technology.

LABOR PRODUCTIVITY

Table 2 also shows that technology combinations are overwhelmingly associated with higher labor productivity levels, as reflected in a relatively large number of positive coefficients (though not all of them are statistically significant). The adoption of advanced manufacturing technologies is not associated with higher rates of labor productivity growth, although the lack of data on technology adoptions prior to 1988 does not allow us to examine this issue as carefully as one might like.

The combinations associated with the highest levels of labor productivity are CAD combined with CAD output used for procurement, and the joint adoption of local area networks, network connections with suppliers and/or contractors, and programmable control technologies (both are associated with 60 percent higher labor productivity than otherwise similar plants that adopt none of the SMT technologies). Interestingly, both of these technology combinations involve the exchange of data within establishments or across firm boundaries, suggesting high returns to greater coordination of design, production, marketing, and other functions. The adoption of factory floor local area networks without any other SMT technology, however, is associated with 28 percent lower labor productivity. This negative association suggests that plants adopted the technology to deal with coordination problems arising from rapid growth.

Finally, again there is no clear evidence of a positive and monotonic relationship between labor productivity levels and the number of technologies adopted. The most technology-intensive plants (those that adopt seven or more SMT technologies) have 21 percent higher labor productivity, but most of the two- and three-technology combinations are associated with even higher levels of labor productivity.

EMPLOYEE EARNINGS

Technology combinations associated with higher labor productivity are also generally associated with higher production worker earnings (see Table A-1). Although this finding is quite plausible, because plants with higher labor productivity tend to pay higher wages, it may be the net result of other factors. Wage differentials, for example, could also result from differences in the proportions of workers with various skills or differences in working conditions that require compensating payments (*e.g.*, skilled machinists may find numerically controlled tools boring to use). Some technologies may enable managers to gain greater control over the production process and to trace errors more easily back to their source and thereby make workers more accountable. This may lead to lower wages because firms will not need to motivate workers by combining relatively high wages with the threat to fire shirking workers. Alternatively, if the adoption of an advanced technology increases the cost to the employer of poor performance (perhaps by damaging expensive equipment or work-in-process), then the adoption of the advanced technology may lead to higher ("efficiency") wages (see Katz 1986).[18]

The combination of CAD with LAN for technical data and factory use, WAN, and programmable manufacturing control technologies is associated with the highest production worker earnings premium (more than 25 percent). Other technology combinations associated with high production worker earnings premia (of about 15 percent each) are: CAD and programmable logic controllers (technologies 1 and 16); CAD, CAD used to control machines, NC, and computers used for control (technologies 1, 2, 5, and 17); CAD and computers used for control (technologies 1 and 17); and combinations of seven or more technologies.

In contrast to the findings for production worker earnings levels, non-production worker earnings exhibit a more ambiguous relationship with the adoption of technologies. For non-production workers, far fewer technology combinations are associated with significantly higher earnings, and far more are associated with significantly lower earnings. The technology associated with the highest non-production worker earnings premium (33 percent) is flexible manufacturing cells. Most of the technology combinations associated with lower non-production worker earnings do not include CAD (although the converse is not necessarily true), suggesting that higher paid design jobs may be located at other establishments within or outside the firm, or that design performed at these establishments uses more relatively low paid non-production workers (for example, draftsmen) than establishments that adopted CAD. The plants that use seven or more technologies pay their non-production workers a modest premium of 5.5 percent, perhaps because relatively few plants that adopt seven or more technologies omit CAD technology. The most technology-intensive plants do not have significantly higher production or non-production worker earnings growth rates than the least technology-intensive plants.[19]

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[18] Since earnings equals the product of average hourly wages and average hours per worker, we also estimate regressions with production worker hours and hourly wages as dependent variables. This permits a decomposition of the technology coefficients in the production worker earnings regression into "effects" on wages and hours. In most cases, the associations between technology combinations and production worker hourly wages appear to account for the bulk of the associations with production worker earnings. Moreover, few of the technology coefficients in the production worker hours regressions were significantly different from zero (although plants with seven or more technologies had significantly more hours per worker). These findings are consistent with the hypothesis that most of the technology combinations that are positively associated with higher production worker earnings and hourly wages may also be associated with higher levels of general rather than firm-specific human capital. Several of the technology combinations had negative and significant coefficient estimates in the production worker hours regression. These technology combinations are generally comprised of CAD and some type of connectivity-related technology: the use of CAD output to control machines or in procurement; local or wide area networks; and computers used for programmable control. All of these technologies are indicative of enhanced integration of the shop floor and engineering and design departments (either within the plant or with another plant). This is consistent with the hypothesis that these technologies require less firm-specific training, perhaps because they permit easier assembly of products.

[19] The coefficient estimates for the control variables are in line with expectations, providing a further check of the validity of our model specification. Older or larger plants, multi-unit plants, and plants with growing capital to labor ratios experience slower production and non-production worker employment growth. Plant size, plant age, multi-unit status, capital to labor ratio, and the price of output are associated with higher levels of production and non-production worker earnings, with the exception of multi-unit status, which is associated with lower non-production worker earnings (perhaps because higher ranking managers are located at other

INTEGRATION OF FABRICATION AND ASSEMBLY OPERATIONS

Statistical tests indicate that there are significant differences in the degrees of associations between technology combinations and plant performance for plants with different types of operations.[20] Tables 3 and 4 display excerpts of regression results, for growth rates and levels of the dependent variables, for subsamples of the data based on type of operations (fabrication, assembly, and both) for three commonly adopted technology combinations, *i.e.*, CAD, NC, and seven or more technologies.[21] Coefficients are also shown for regressions based on the overall sample (drawn from Tables A-1 and A-2).

Plants that adopt at least seven technologies appear to have higher total employment growth rates than plants that adopted no SMT technology. This is especially so for fabricators or assemblers, rather than integrated operations. The integrated plants that adopt CAD or NC as stand-alone technologies, however, have significantly higher non-production worker employment growth rates than integrated plants that adopt no SMT technology, in contrast to the assembly and fabrication plants.

Labor productivity levels at integrated plants that adopt CAD (with or without NC), the combination of CAD, CAD/CAM and NC, or the combination of CAD, NC, and LAN for technical data are at least 18 percent higher than at integrated plants that did not adopt any SMT technology and in most cases are also considerably higher than in corresponding plants that engage in only fabrication or assembly. A similar story holds for production worker earnings levels and growth rates.

None of the technology coefficients from the non-production worker earnings levels or growth rates regressions shown in Table 3 are statistically significant for the single operation plants. In contrast, the most technology-intensive integrated plants have significantly higher levels of non-production worker earnings, and significantly lower growth rates of non-production worker earnings, than plants that adopted no SMT technology.

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plants or at administrative establishments). Higher labor productivity is associated with multi-unit status, product price, and plant size, but not with plant age. The plant capital to labor ratio is associated with significantly higher levels and growth rates of labor productivity and production and non-production earnings.

[20] To implement the tests, we introduce additional explanatory variables by interacting all of the technology variables and the other control variables (except the industry and region dummies) with dummy variables corresponding to whether or not the plant engaged in assembly or fabrication. In other words, the base against which the other production processes are compared is the combinations of both fabrication and assembly. The hypothesis that the assembly interactions, the fabrication interactions, or both were all equal to zero can be rejected at the 99 percent level of confidence in almost all cases (except for the assembly interactions in the non-production worker earnings growth rate regression).

[21] The regressions for the fabrication, assembly, and both fabrication and assembly subsamples have a specification similar to the overall regressions and are available upon request.

Table 3:
Excerpted 1982-87 Growth Rate Regression Coefficient Estimates for the Adoption of Selected Advanced Manufacturing Technology Combinations

	Overall Sample			Fabrication Plants			Assembly Plants			Fabrication and Assembly		
Dependent Variables:	CAD	NC	7+	CAD	NC	7+	CAD	NC	7+	CAD	NC	7+
Total Employment	.049	.040	.094**	.070	.048	.117*	.051	(D)	.151**	.047	.044	.077**
Production Worker Employment	-.015	.026	.111**	.093	.017	.107	.018	(D)	.211**	.007	.041	.091**
Non-production Worker Employment	.104**	.097**	.086**	.072	.097	.096	.091	(D)	.141	.102*	.108*	.072
Labor Productivity	-.040	-.065	.065*	-.236	-.226**	.091	-.206**	(D)	.037	.094	-.012	.097*
Production Worker Earnings	.058**	.051*	.032	.032	-.069	-.099	.031	(D)	-.010	.025	.090**	.059**
Non-production Worker Earnings	-.040	-.093**	-.033	.260	-.093	.126	-.100	(D)	-.031	-.077	-.124**	-.086**

CAD = adoption of computer aided design only; NC = adoption of numerically (or computer numerically) controlled tools only; 7+ = adoption of seven or more technologies. * = significant at 5%; ** = significant at 1%. Overall sample coefficient estimates drawn from Tables A-1 and A-2. Operations subsample coefficient estimates drawn from separate regressions with specifications similar to that used for the overall sample regressions.

Table 4:
Excerpted 1987 Levels Regression Coefficient Estimates for the Adoption of Selected Advanced Manufacturing Technology Combinations

	Overall Sample			Fabrication Plants			Assembly Plants			Plants Engaged in Both Fabrication and Assembly		
Dependent Variables:	CAD	NC	7+	CAD	NC	7+	CAD	NC	7+	CAD	NC	7+
Production Worker Earnings	.100**	.074**	.147**	.069	.053	.133**	.036	.173	.090*	.113**	.071**	.154**
Non-production Worker Earnings	-.021	-.064**	.055**	.318	-.153	.006	-.025	-.076	.046	-.022	-.047	.054*
Labor Productivity	.051	.076*	.188**	-.219	-.027	.112	-.047	-.062	.229**	.201**	.117**	.243**

Note: see note to Table 3.

V. CONCLUDING REMARKS

Building on previous work using the 1988 Survey of Manufacturing Technology and the Longitudinal Research Database, we examine the relationships between the adoption of specific technology combinations and various measures of plant performance. We find a high degree of heterogeneity in the pattern of technology adoption and significant differences in the relationships between specific technology combinations and employment growth, earnings growth and levels, and labor productivity levels. The monotonic relationships between the number of technologies adopted and plant performance found in earlier studies mask a richer story of variation in the magnitude and sign of these relationships, depending on specific technology combinations.

The associations between advanced technologies and plant performance also differ depending on the type of plant operations. One explanation for this finding is that plants that engage in both fabrication and assembly and that use advanced technologies may forgo fabricating parts at lowest possible cost if designing parts for ease of assembly reaps more than offsetting cost savings. These gains would be reflected in some of our findings showing that technologies are associated with higher levels and growth rates of labor productivity and higher production worker earnings for integrated plants than for non-integrated plants. The adoption of advanced technologies combined with greater integration of fabrication and assembly may also result in slower growth in non-production worker employment (since fewer assembly engineers would be needed).[22]

Our findings on integrated manufacturing are consistent with claims that achieving the full potential of advanced technologies requires close cooperation between design, fabrication, assembly, inspection, field maintenance, engineering, and marketing departments (see, for example, Duimering, *et al.*, 1993 and Womack and Jones, 1994).[23] Further efforts in data

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[22] This is not to say that all integrated plants perform better than non-integrated plants. In the overall sample regressions (see Table A-1), integrated plants have significantly lower labor productivity than plants that engaged only in fabrication, all else equal, perhaps because integrated plants incur higher coordination costs than unintegrated plants.

[23] Alternatively, a set of small firms could vertically integrate by closely coordinating their marketing, design, inventory control and quality management operations, thereby creating a larger “virtual corporation” (see Davidow and Malone) and reaping some of the same benefits as a single firm that closely integrates its operations. The one SMT technology that may be indicative of interfirm coordination is the wide area network for exchange of data between customers and/or suppliers (technology 15), which appears in

collection and research are needed on these “soft technologies,” *i.e.*, managerial innovations that complement the “hard technologies” studied in this report.

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several cases to be associated with higher levels of labor productivity, production worker earnings, and production worker employment growth (see Tables A-1 and A-2).

[23] The possible advantages include achieving faster design, avoiding component features that are excessively costly to make, and minimizing materials costs and work-in-process inventories. Thus, it appears that plants that engage in assembly and fabrication operations within the same plant are more apt to integrate their operations than plants that engage in either assembly or fabrication (but not both).

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APPENDIX A:
DETAILED REGRESSION ESTIMATES

Table A- 1:
1987 Levels Regressions: Labor Productivity and Earnings

		Dependent Variables		
Independent Variables	Cell Counts or Means	Labor Productivity	Non-prod Worker Earnings	Production Worker Earnings
1	294	0.051	-0.021	0.100**
2	(D)	+(D)	-(D)	+(D)
3	(D)	+(D)	+(D)	+(D)
4	12	-0.175	0.327**	-0.100
5	274	0.076*	-0.064**	0.074**
13	23	-0.017	0.102	0.054
14	14	-0.326*	-0.139	-0.132
15	59	0.216**	0.077	0.125**
16	99	0.073	-0.047	0.050
17	62	-0.044	-0.146**	-0.019
other 1's	40	-0.019	-0.194**	-0.093
1, 5	144	0.234**	0.015	0.101**
5, 16	61	0.089	0.020	0.111**
2, 5	28	0.086	-0.180**	0.014
5, 17	40	-0.031	0.030	0.083*
16, 17	56	0.147*	-0.065	0.011
1, 16	49	0.253**	0.067	0.158**
1, 13	34	0.212*	-0.008	0.022
1, 3	26	0.474**	-0.009	-0.086
1, 17	32	0.196	0.079	0.143*
15, 16	27	0.072	-0.352**	0.083
other 2's	275	0.149**	-0.020	0.114**
1, 2, 5	76	0.112*	-0.020	0.125**
5, 16, 17	48	0.243**	-0.016	0.133**
1, 5, 16	53	0.045	0.005	0.113**
1, 5, 17	35	-0.007	-0.039	0.058
1, 13, 14	20	0.059	0.213*	0.106
1, 16, 17	25	0.247*	0.055	0.050
1, 5, 13	15	0.253	0.189*	0.122
1, 13, 16	10	0.067	0.013	+(D)
5, 13, 14	(D)	+(D)	+(D)	+(D)
5, 15, 17	10	0.245	0.080	-0.105
other 3's	405	0.107**	-0.043	0.098**
1, 5, 16, 17	66	0.070	0.085	0.024
1, 2, 3, 5	16	0.146	-0.152*	0.128*
1, 2, 5, 17	28	0.135	0.053	0.148**
1, 2, 5, 16	26	0.123	0.043	0.055
1, 5, 13, 16	20	0.069	0.041	0.165*
2, 5, 16, 17	(D)	-(D)	-(D)*	-(D)*
13, 14, 16, 17	12	0.139	0.060	0.061
1, 5, 15, 16	15	0.091	0.026	0.019

Table A- 1:
1987 Levels Regressions: Labor Productivity and Earnings

		Dependent Variables		
Independent Variables	Cell Counts or Means	Labor Productivity	Non-prod Worker Earnings	Production Worker Earnings
1, 13, 14, 17	17	0.132	0.076	-0.075
5, 15, 16, 17	(D)	+(D)*	+(D)	+(D)
other 4's	429	0.170**	0.014	0.083**
1, 2, 5, 16, 17	25	0.174	-0.038	0.132
5, 13, 14, 16, 17	11	-0.093	-0.525**	0.109
1, 2, 3, 5, 16	(D)	-(D)	+(D)	-(D)
1, 5, 15, 16, 17	10	0.044	0.171	0.022
13, 14, 15, 16, 17	10	0.473**	-0.028	-0.070
1, 2, 5, 13, 16	(D)	-(D)	+(D)	-(D)
1, 2, 3, 5, 17	(D)	+(D)	+(D)	+(D)*
1, 2, 5, 14, 17	(D)	+(D)	-(D)*	+(D)
1, 13, 14, 16, 17	(D)	+(D)	+(D)*	+(D)
1, 2, 3, 4, 5	(D)	+(D)	-(D)*	-(D)
other 5's	428	0.161**	0.021	0.099**
1, 2, 3, 5, 16, 17	15	0.107	0.264*	-0.060
1, 5, 13, 14, 16, 17	14	0.216	0.099	0.138
5, 13, 14, 15, 16, 17	(D)	+(D)	-(D)	+(D)
1, 2, 5, 13, 14, 16	10	0.313	0.140	0.195
1, 2, 3, 4, 5, 16	(D)	-(D)	+(D)	+(D)
1, 5, 13, 14, 15, 16	(D)	+(D)	+(D)*	+(D)
1, 2, 5, 13, 16, 17	(D)	-(D)	-(D)	-(D)
1, 4, 5, 13, 14, 17	(D)	+(D)	+(D)	+(D)
1, 2, 5, 11, 12, 16	(D)	+(D)*	-(D)	+(D)
1, 13, 14, 15, 16, 17	10	-0.277	-0.003	0.252*
other 6's	409	0.126**	0.015	0.114**
7 or more	1,537	0.188**	0.055**	0.147**
log capital-labor ratio	3.105	0.139**	0.057**	0.088**
multi-unit firm	0.628	0.129**	-0.072**	0.020*
plant age = 5 to 15 years	0.304	0.008	0.071**	0.017
plant age = 16 to 30 years	0.309	-0.032	0.065**	0.044*
plant age = over 30 years	0.290	-0.049	0.087**	0.079**
assembly	0.187	-0.016	-0.025	-0.124**
fabrication and assembly	0.627	-0.051**	-0.012	-0.067**
neither fabrication nor assembly	0.052	0.072	-0.084**	-0.060**
ave. product price = \$5 to \$100	0.262	0.039	0.025	0.028*
ave. price = \$101 to \$1,000	0.215	0.085**	0.024	0.139**
ave. price = \$1,001 to \$2,000	0.056	0.187**	0.080**	0.247**
ave. price = \$2,001 to \$10,000	0.123	0.140**	0.033	0.256**
ave. price = over \$10,000	0.199	0.125**	0.112**	0.305**
total employment = 100 to 249	0.268	-0.016	0.004	-0.026*
total employment = 250 to 499	0.131	-0.018	-0.009	0.037*
total employment = 500 to 999	0.106	0.077	0.012	0.063**
total employment = 1,000 - 2,499	0.049	0.110*	0.092*	0.146**
total employment = 2,500+	0.025	0.252**	0.115*	0.267**
dependent variable means		3.879	3.449	2.966
adj R^2		0.186	0.099	0.382

N=6,736. * = significant at 5%; ** = significant at 1%; (D) = suppressed to prevent disclosure of confidential data. Numbers used to identify technologies (1-17) are defined in Appendix C. The numbers in the second column are the number of plants with the technology combination listed in the first column or are sample means for control variables.

Table A- 2:
1982-87 Growth Rate Regressions: Productivity, Earnings, and Employment

Independent Variables	Cell Counts or Sample Means	Dependent Variables					
		Labor Productivity	Non-production Worker Earnings	Production Worker Earnings	Non-production Worker Employment	Production Worker Employment	Total Employ-ment
1	289	-.040	-.040	.058**	.104**	-.015	.049
3	(D)	(D)	(D)	(D)	-(D)*	(D)	-(D)*
4	13	.038	.443**	-.160*	-.732**	.182	-.019
5	279	-.065	-.093**	.051*	.097**	.026	.040
13	21	.212	.073	.006	.052	-.190	-.075
14	11	-.447*	.135	-.120	.017	.347**	.266**
15	62	-.090	.036	-.013	.086	.089	.090*
16	99	-.077	-.035	.002	.069	.145**	.120**
17	57	.047	-.056	.060	.030	-.043	-.040
other 1’s	51	-.010	.005	.018	.012	.014	-.022
1, 5	152	.018	-.038	.037	-.030	.098**	.075**
5, 16	77	-.009	.083	.057	.040	.116**	.106**
2, 5	28	.029	-.088	.012	-.031	.145*	.074
5, 17	45	-.111	.066	.050	.045	.053	.041
16, 17	50	.209*	.054	.068	-.165	.038	-.044
1, 16	51	.076	-.048	.056	-.110	-.128*	-.046
1, 13	31	-.040	.081	-.140*	.124	.317*	.230**
1, 3	20	.391**	-.320**	-.118	.170	-.380**	-.193**
1, 17	29	-.003	.090	-.014	.076	.030	.069
15, 16	28	-.250	-.085	.151*	.154	.168	.171*
other 2’s	263	.100*	-.033	.049*	-.040	.036	.018
1, 2, 5	72	.133*	.003	.037	.057	.034	.036
5, 16, 17	49	.051	-.001	.084*	.012	-.066	-.069
1, 5, 16	59	.034	-.051	.040	-.008	.162**	.094
1, 5, 17	34	.074	.175*	-.0002	.061	.086	.076
1, 13, 14	19	-.020	.120	.031	.064	.260*	.150
1, 16, 17	30	.056	.008	-.052	.332**	-.038	.128
1, 5, 13	18	.042	.054	.004	.271*	.074	.105
1, 13, 16	10	.057	.090	.115	.163	.117	.090
5, 13, 14	11	-.014	-.087	.010	-.003	.063	.005
5, 15, 17	(D)	(D)	(D)	-(D)*	(D)	(D)	(D)
other 3’s	420	-.023	-.018	-.0004	.012	.080**	.059**
1, 5, 16, 17	66	-.008	-.097	.031	.133	.194**	.147**
1, 2, 3, 5	20	-.079	-.244**	.006	.288**	.016	.062
1, 2, 5, 17	28	.083	-.177	.023	.112	.018	.040
1, 2, 5, 16	20	-.164	-.067	.083	-.026	.171	.089
1, 5, 13, 16	18	.180	-.119	.156	.123	.015	.060
2, 5, 16, 17	11	.388**	-.393**	-.139*	.146	-.028	-.026
13, 14, 16, 17	13	-.277	-.057	.099	.160	.217	.206*
1, 5, 15, 16	15	-.185	.046	-.053	-.103	.234*	.112
1, 13, 14, 17	17	-.130	.039	-.096	.176	.234	.175
other 4’s	418	.067	.019	.053**	.042	.047	.034
1, 2, 5, 16, 17	26	.009	.028	.078	-.005	.147	.117
5, 13, 14, 16, 17	12	-.004	-.212	.080	.360*	.050	.148
1, 2, 3, 5, 16	(D)	(D)	(D)	(D)	-(D)*	(D)	-(D)*
1, 5, 15, 16, 17	13	-.093	.089	-.002	.010	.103	.073
13, 14, 15, 16, 17	11	.259	-.082	-.134	-.056	-.100	-.090
1, 2, 5, 13, 16	(D)	-(D)*	(D)	-(D)*	(D)	+(D)*	+(D)*
1, 2, 3, 5, 17	(D)	(D)	(D)	(D)	(D)	-(D)*	-(D)*
1, 2, 5, 14, 17	(D)	(D)	-(D)*	(D)	(D)	(D)	(D)

Table A- 2:
1982-87 Growth Rate Regressions: Productivity, Earnings, and Employment

Independent Variables	Cell Counts or Sample Means	Dependent Variables					
		Labor Productivity	Non-production Worker Earnings	Production Worker Earnings	Non-production Worker Employment	Production Worker Employment	Total Employ-ment
1, 13, 14, 16, 17	10	.063	.831**	.060	-.398*	.191	-.042
1, 2, 3, 4, 5	(D)	(D)	-(D)*	(D)	(D)	(D)	(D)
other 5's	443	.076*	-.004	.023	.047	.085**	.064**
1, 2, 3, 5, 16, 17	19	.026	.095	.094	-.039	.092	.048
1, 5, 13, 14, 16, 17	13	.119	.054	-.072	.138	.193	.144
1, 2, 5, 13, 14, 16	12	.031	.090	-.014	.290	.281*	.265*
1, 2, 3, 4, 5, 16	(D)	(D)	(D)	-(D)*	(D)	+(D)*	(D)
1, 5, 13, 14, 15, 16	(D)	(D)	+(D)*	(D)	-(D)*	(D)	(D)
other 6's	411	.133**	.078*	.047*	.072	.067*	.068**
7 or more	1,541	.065*	-.033	.032	.086**	.111**	.094**
change in log output	.334	N/A	N/A	N/A	.548**	.625**	.608**
log capital/labor ratio	1.620	.114**	.044**	.068**	-.079**	-.132**	-.123**
multi-unit firm	.606	.031	.009	-.012	-.113**	-.055**	-.067*
plant age = 5 to 15 years	.295	.001	.054*	.054**	-.065*	-.030	-.046**
plant age = 16 to 30 years	.321	-.015	.027	.055**	-.141**	-.101**	-.126**
plant age = over 30 years	.311	-.062	-.012	.037*	-.137**	-.097**	-.118**
assembly plant	.174	.050	.037	.029	.059*	-.081**	-.031
fabrication and assembly	.639	-.005	.035*	.001	.032	.026	.019
neither fabrication nor assembly	.055	.070	-.021	-.015	.050	-.048	-.019
ave. product price = $5 to $100	.265	.017	.019	-.009	-.061*	.010	-.006
ave. price = $101 to $1,000	.214	-.001	-.002	-.009	-.024	-.016	-.015
ave. price = $1,001 to $2,000	.055	.066	.025	.025	-.019	-.066*	-.048*
ave. price = $2,001 to $10,000	.123	-.069*	-.009	-.001	-.036	-.030	-.016
ave. price = over $10,000	.197	-.053	.026	-.009	.047	-.082**	-.016
total employment = 100 to 249	.222	-.058*	.021	.009	-.133**	-.106**	-.113**
total employment = 250 to 499	.125	-.045	.015	.014	-.132**	-.153**	-.145**
total employment = 500 to 999	.095	-.050	.040	-.013	-.240**	-.153**	-.180**
total employment = 1,000 to 2,499	.057	-.013	.087	.020	-.250**	-.204**	-.202**
total employment = 2,500 or more	.028	.033	.052	.018	-.322**	-.215**	-.231**
dependent variable means		.192	.227	.239	.156	.115	.142
adj R^2		.109	.040	.059	.387	.579	.684

N=6,851. * = significant at 5%; ** = significant at 1%; (D) = suppressed to prevent disclosure of confidential data. The numbers used to identify technologies (1-17) are defined in Appendix C.

APPENDIX B: DEFINITIONS OF VARIABLES USED IN THE REGRESSION ANALYSES

A. *Definitions of dependent variables:*

1. Rate of growth of production worker employment = natural logarithm of production worker employment in 1987 minus log(production worker employment in 1982).
2. Rate of growth of non-production worker employment = log(non-production worker employment in 1987) minus log(non-production worker employment in 1982).
3. Total employment growth rate = log(total employment in 1987) minus log(total employment in 1982).
4. Labor productivity level = log(total annual value added at plant in 1987 divided by 1987 total employment).
5. Labor productivity growth rate = log(total annual value added at plant in 1987 divided by 1987 total employment) minus log(total annual value added at plant in 1982 divided by 1982 total employment).
6. Production worker earnings level = log(total annual production worker cash wage bill in 1987 divided by number of production workers in 1987).
7. Production worker earnings growth rate = log(total annual production worker wages in 1987 divided by number of production workers in 1987) minus log(total annual production worker wages in 1982 divided by number of production workers in 1982).
8. Non-production worker earnings level = log(total annual non-production worker cash wage bill in 1987 divided by number of non-production workers in 1987).
9. Non-production worker earnings growth rate = log(total annual non-production worker cash wage bill in 1987 divided by number of non-production workers in 1987) minus log(total annual non-production worker cash wage bill in 1982 divided by number of non-production workers in 1982).

B. 67 technology dummy variables that were included in regressions (Appendix C provides the names and brief definitions of the technologies that correspond to numbers 1 through 17):

1. The following single technology variables for plants with exactly one technology: 1; 2; 3; 4; 5; 13; 14; 15; 16; 17.

2. The following technology pairs for plants with exactly two technologies: 1,5; 5,16; 2,5; 5,17; 16,17; 1,16; 1,13; 1,3; 1,17; 15,16.

3. The following technology triplets for plants with exactly three technologies: 1,2,5; 5,16,17; 1,5,16; 1,5,17; 1,13,14; 1,16,17; 1,5,13; 1,13,16; 5,13,14; 5,15,17.

4. The following technology quadruplets for plants with exactly four technologies: 1,5,16,17; 1,2,3,5; 1,2,5,17; 1,2,5,16; 1,5,13,16; 2,5,16,17; 13,14,16,17; 1,5,15,16; 1,13,14,17; 5,15,16,17
5. The following technology quintuplets for plants with exactly five technologies: 1, 2, 5, 16, 17; 5, 13, 14, 16, 17; 1, 2, 3, 5, 16; 1, 5, 15, 16, 17; 13, 14, 15, 16, 17; 1, 2, 5, 13, 16; 1, 2, 3, 5, 17; 1, 2, 5, 14, 17; 1, 13, 14, 16, 17; 1, 2, 3, 4, 5
6. The following technology 6-tuplets for plants with exactly six technologies: 1, 2, 3, 5, 16, 17; 1, 5, 13, 14, 16, 17; 5, 13, 14, 15, 16, 17; 1, 2, 5, 13, 14, 16; 1, 2, 3, 4, 5, 16; 1, 5, 13, 14, 15, 16; 1, 2, 5, 13, 16, 17; 1, 4, 5, 13, 14, 17; 1, 2, 5, 11, 12, 16; 1, 13, 14, 15, 16, 17

7. If a plant that adopted n technologies did not adopt any of the ten explicitly listed n-technology combinations (n=1,2,3,4,5,6), then an dummy variable called “other n’s” took the value of one; otherwise “other n’s” took the value of zero. A single dummy variable for whether a plant adopted 7 or more technologies was also included.

C. *Other control variables:*

1. Plant size:
   total employment 20-99 (omitted from regression)
   total employment 100-249
   total employment 250-499
   total employment 500-999
   total employment 1,000-2,499
   total employment greater than or equal to 2,500

2. Multi-unit firm = plant owned by a firm with more than one manufacturing plant.

3. Plant age:
   less than 5 years (omitted)
   5 to 15 years
   16 to 30 years
   over 30 years

4. Type of operations at plant:
   fabrication (omitted)
   assembly
   both fabrication and assembly
   neither fabrication nor assembly

5. Average market price for most products:
   less than $5 (omitted)
   $5 to $100
   $101 to $1000
   $1001 to $2000
   $2001 to $10000
   over $10000

6. Four digit industry dummy variables (coefficient estimates not shown).

7. Nine census region dummy variables (coefficient estimates not shown).

8. log(book value of capital per worker in 1987); for the growth rate regressions, log(book value of capital per worker in 1987) minus log(book value of capital per worker in 1982).

9. log(output in 1987) minus log(output in 1982), employment regressions only.

APPENDIX C:
DESCRIPTIONS OF THE TECHNOLOGIES SURVEYED IN THE 1988 SMT

A. *Computer Aided Design and Related Technologies.*

1. Computer-aided design and/or computer-aided engineering (CAD).

CAD is the use of computers to design, analyze, and test (through simulations) parts or assembled products (U.S. Bureau of the Census 1989, p. A-1).

2. CAD output used to control machines in computer-aided manufacturing (CAM).

CAM is the use of CAD-generated part design data to control the machines used to manufacture the part. CAD systems can generate a keypunched tape or computer programs that can instruct a numerically controlled machine tool on how to create the CAD-designed part (U.S. Congress 1984, p. 45).

3. Digital representation of CAD output used in procurement activities.

Although CAM generally is used with CAD at the plant, some plants may use the digital representation of a part from another plant's CAD output to manufacture the part. For example, some electronics firms use CAD to design application-specific integrated circuits and give the CAD output to contractors that specialize in quick manufacture of the chips (Davidow and Malone 1992, p. 40).

B. *Flexible Manufacturing*

4. Flexible manufacturing cells (FMC).

Flexible manufacturing cells (FMC) are computer-controlled groups of machine tools with automated material handling. Some manufacturers make small batches of many different parts using many different materials. Under these conditions, traditional plant layout segregating types of machines (lathes, grinders, drills, etc.) may not be as efficient as using FMC/FMS to permit machines and workers to specialize in families of similar parts. Advocates of cellular manufacturing claim it reduces materials handling, set-up time, and work-in-process inventories (Bedworth, et al. 1991, p. 205).

5. Numerically or computer numerically controlled machines (NC).

Conventional machine tools are used to cut and form materials and are guided by a skilled machinist, who manipulates either the workpiece or the cutting tool to produce the intended shape of the part, and who controls the speed of the cut and the flow of coolant (U.S. Congress 1984, p. 57). Numerically controlled machines cut and form parts using programmed instructions, motors to position parts and tools, and controllers to receive and implement the programmed commands, which can consist of prepunched mylar tapes (in NC machines) or software in a microcomputer (in the case of CNC). NC has been applied to other manufacturing processes such as sheet metal press operations, welding, assembling, and quality inspection. CNC capability can be retrofitted to older NC equipment using programmable controllers or computers used for control (technologies 16 and 17) at far less cost than purchasing new CNC equipment (Bedworth, et al. 1991, p. 461). Thus plants that adopt technologies 5 and 16 or 17 might be using CNC rather than NC.

NC has several advantages over conventional equipment. It makes it easier to machine complex parts; once a program is written, it can be edited to make similar parts; it requires fewer fixtures and setups; and finally it affords predictability: better control over shop operations, more accurate production cost estimates for bidding, and more reliable estimates of delivery times (U.S. Congress 1984, p. 185). NC is particularly suited to small (50-75 or fewer similar parts) batch production (Bedworth, et al. 1991, p. 468); larger batches may be more economically fabricated with specialized machines (U.S. Congress 1984, p. 37). Shortages of skilled machinists in the late 1970s and early 1980s have been cited as a stimulus for the adoption of NC or CNC, as these machines do not require highly skilled operators (U.S. Congress 1984, pp. 136-137).

6. **Materials working lasers.**

Materials working lasers are used for welding and cutting sheets of metal. Numerically controlled lasers can cut complex shapes at rapid speeds and are very flexible.

C. *Robotics*

7. **Pick and place robots.**
8. **Other robots.**

Industrial robots consist of three components: a microelectric programmable controller that steers the robot through its motions; a manipulator comprised of the robot's base, an actuation mechanism (the device that moves the robot's arm), and the robot's arm; and an "end-effector," which is the tool the robot uses to execute its job (U.S. Congress 1984, p. 50). Robots are usually programmed by physically guiding them through their tasks. These motions are recorded by the robot's controller. Increasingly, robots are programmed "off-line", where a computer programmer writes programming code for the robot (Bedworth et al. 1991, pp. 546-547).

Pick and place robots are well-suited to materials handling and machine loading and unloading, which are labor-intensive tasks requiring strength and dexterity (Bedworth, et al. 1991, pp. 505-506). Successful assembly of components by pick and place robots requires careful parts alignment. Components designed for human assembly generally need to be redesigned for robotic assembly (*e.g.*, by making the components as symmetric as possible to minimize the need for the robot to re-orient them). Robotic assembly lines require uniform assembly rates, since they cannot adapt as readily to variations in assembly times as humans (*Ibid.*, pp. 506-516).

"Other robots" are used as spray painters, welders, drills, sanders, etc., all tasks that can be unpleasant or dangerous to humans.

D. Automated Materials Handling

9. Automatic storage and retrieval systems (AS/RS)

AGVS refers to vehicles equipped with programmable automatic guidance devices that convey materials, tools, parts, or products between work stations (U.S. Bureau of the Census 1989, p. A-1).

10. Automatic guided vehicle system (AGVS)

AS/RS is "computer controlled equipment providing for the automatic handling and storage of materials, parts, subassemblies, or finished products" (U.S. Bureau of the Census 1989, p. A-1). AS/RS essentially is "an automated warehouse where parts are stored in racks and retrieved on computerized carts and lift trucks" (U.S. Congress 1984, p. 66). The alleged advantages of AS/RS include reduced space requirements and more accurate inventory recordkeeping (*Ibid.*, p. 67).

E. Automated Sensors

11. Automatic sensor-based inspection and/or test equipment for incoming or in process materials.

12. Automatic sensor-based inspection and/or test equipment for final product.

Computer-aided inspection generally consists of small computer devices that can measure various attributes of a part (*e.g.*, dimensions) and store them in digital form until they are loaded into another computer for statistical analysis and report generation.

F. Communications Networks

13. Local area network for technical data.

Local area networks (LAN) permit private, direct communications between programmable machines and computers. Technology 13 is defined as use of local area networks to exchange technical data within design and engineering departments (U.S. Bureau of the Census 1989, p. A-1). A LAN for technical data may facilitate the exchange of CAD designs between design engineers, especially when large numbers of similar parts are produced in small batches, thereby saving effort in finding and adapting earlier designs to new products. LAN for technical data may also help to more closely integrate design and manufacturing engineering functions within a plant.

14. Local area network for factory use.

Technology 14 is the exchange of information between different points on the factory floor using local area networks (U.S. Bureau of the Census 1989, p. A-1). LANs on the factory floor connect programmable machines and flexible machine cells to achieve computer-integrated manufacturing (CIM) (*Ibid.*, p. 422).

15. Intercompany computer network linking plant to subcontractors, suppliers, and/or customers.

Technology 15 is a computer network linking a manufacturing plant with suppliers and/or customers, permitting the sharing of data on marketing, design, and quality control.

G. Programmable Manufacturing Control

16. Programmable logic controllers (PLC).

Programmable manufacturing control gathers physical information, converts the information into digital format, and uses it to monitor, analyze, and regulate manufacturing processes. Technology 16 is “a solid state industrial control device that has programmable memory for storage of instructions, which performs functions equivalent to a relay panel or wired solid state logic control system” (U.S. Bureau of the Census 1989, p. A-1). Relay panels or solid state logic control systems perform the same functions as programmable controllers but are less flexible than programmable controllers, which can be reprogrammed to monitor and control new processes (Bedworth, et al. 1991, p. 389).

17. Computer(s) used for control on the factory floor.

Technology number 17 “exclude[s] computers imbedded within machines, or computers used solely for data acquisitions or monitoring [but includes] computers that may be dedicated to control, but which are capable of being reprogrammed for other functions” (U.S. Bureau of the Census 1989, p. A-1). Thus, technology 17 is similar to, but more flexible than, technology 16. For example, computers can be programmed with higher level computer languages, with which engineers (as opposed to technicians) may be more familiar. Computers are more network compatible than programmable controllers and are thus better able to participate in computer integrated manufacturing (Bedworth, et al. 1991, p. 403).