The Strategic Investment in Information Technologies and New Human Resource Practices and Their Effects on Productivity: An "Insider" Econometric Analysis

Ann Bartel
Columbia Business School and NBER

Casey Ichniowski
Columbia Business School and NBER

Kathryn Shaw
Stanford Business School and NBER

July 2004

Paper prepared for presentation at the National Bureau of Economic Research Summer Institute, August 6, 2004. We thank Ricardo Correa and Yoonsoo Lee for outstanding research assistance on this project.

I. Introduction

Computer-based information technologies were widely adopted by U.S businesses in the 1990's. During the latter half of the 1990's, the rate of investment in computers and software grew at an extraordinary rate of 28% per year. The decline in the cost of computing behind this trend has been equally dramatic. In the last twenty years, the cost of a computer performing one million instructions per second fell from $100 to less than 20 cents today (Council of Economic Advisers, 2001). Many analysts point to the widespread adoption of new computer aided information technologies (IT) as an important cause for the rapid rates of productivity growth experienced by the U.S. in the last decade,[1] as well as for many other trends over this period that have dramatically reshaped the U.S. economy including widespread changes in the organization of work and an increasing demand for new kinds of employee skills.[2]

Several recent studies find evidence that IT investments have contributed to macroeconomic gains in productivity (Jorgenson, Ho, and Stiroh, 2003; Oliner and Sichel, 2000), and that the effects of new IT investments on productivity are concentrated in businesses that adopt new team-based work practices (Bresnahan, Brynjolfson, and Hitt, 2002). Yet, much of the existing research is based on aggregate data that examines the timing of IT investments and the timing of productivity changes for the economy or for broad industry groupings. Firm-level research is less common and analysis here is often based on cross-industry surveys, forcing analysts to examine general measures of IT that may have very different effects in different industrial settings. Missing from the existing empirical literature on the effects of IT on productivity, work organization and worker skills are studies that identify what IT really means in the context of specific production processes with tests of the effects of new IT investments

[1] Productivity growth between 1995 and 2000 averaged 2.5% per year, well beyond what any pre-1995 trend what have predicted, while productivity growth since 2000 continues to outpace the rate of productivity growth that is typical for similar points in the business cycle.
[2] For research on new HRM practices, see especially Osterman (1994, 2000); and on changes in skills demanded by businesses (Black and Lynch, 2001; Autor, Levy and Murnane, 2003). Levy and Murnane (1992) provide one review of the extensive literature on increasing U.S. wage inequality.

on the efficiency and organization of those production processes.[3] While analysis of rich industry-specific data would of course be limited in terms of generalizability, such analysis provides an opportunity to make particularly persuasive empirical tests of the connection between IT and productivity,[4] and if such a relationship exists, a greater understanding of how the businesses have changed to realize those productivity gains.

This paper fills this gap in the literature by conducting an in-depth study of the determinants of productivity in a specific manufacturing production process – valve making. Using personally collected longitudinal data on specific IT investments, productivity measures, work practices, and worker skills for plants in this industry, we present a series of very straight forward empirical estimates that examine how investments in IT and new HRM practices affect the production process in this industry.

The central argument we test is that the adoption of new IT changes the business strategy of the production unit. Adopting new IT will itself change how a company competes. New IT embodies a shift away from strategies that emphasize being a low cost producer of a standardized product toward strategies that emphasize being a higher revenue producer that makes more customized products that meet specific needs of different customers. The paper investigates the effects of the adoption of new IT on product specialization, as well as the effects of IT on the specific aspect of operations that permits this shift in strategy – that is, changes in the time it takes to switch production from one product variety to another. Finally, the paper examines whether IT adoption is accompanied by a change in work practices inside the plant or in the worker skills needed when new machinery is adopted.

The next section presents a model of the decisions to invest in new IT equipment and the relation of IT to product specialization and operating efficiency. Part III describes the valve making industry, the sample of valve making plants that we analyze, and the industry-specific survey we developed to measure productivity, IT and work practices in this setting. Part IV describes trends in IT investments, productivity, and the adoption of new work practices in the industry. Part V presents estimates of changes in

[3] One exception is Hubbard (2003) who analyzes the effects of adopting new on-board truck monitoring technologies on the efficiency and operations in trucking.

[4] See Bartel, Ichniowski and Shaw (2004) for a review of the types of data that researchers have used for estimating organization-level production functions.

specialization in the valve making industry and the effects of IT investments on specialization. In Part VI, we present estimates of conventional productivity models using data from the Census of Manufacturers Longitudinal Research Database for the set of establishments in our survey as a comparison to the analysis we conduct with our own plant-level survey data. Part VII presents empirical estimates of the relationship between information technology and productivity at various stages of the valve-making production process. This section also documents the impact of information technology on worker skills and new HRM practices. Part VIII considers potential sources of bias in the empirical estimates including selectivity in the adoption of IT investments. Part IX concludes.

The empirical findings of the paper reveal a complex web of changes that occurs as manufacturers adopt new IT-aided production equipment. New IT changes how the firm competes and expands the range of product varieties it produces. New IT allows this because of gains in operational efficiency, especially the efficiency of switching production operations over from one product variety to another. Finally, the adoption of new computer-aided production technologies also changes worker skills and new HRM practices as well. The adoption of new IT machinery entails much more than the installation of new equipment on the factory floor.

II. The Strategic Investment in IT and HR Practices

In many manufacturing industries, products are made in batches. For example, in the chemical industry, making a new compound requires a new batch; in publishing, each book is made in its own batch; and in mass-produced furniture-making, each new piece of furniture is a new batch. In each case, the same equipment is used to manufacture the different product types, but the new product specifications require reconfiguring the specific operations of the machines. In these settings, the setup time when machines are reconfigured from the requirements of one product run to the next is a large part of overall production time.

We posit that an important consequence of the dramatic reductions in the price of information technology and the corresponding increases in new computer-aided production equipment is that setup costs are dramatically lower after firms adopt new production machinery. Previously, switchovers between product runs entailed a great deal of hands-on adjustments of machinery by knowledgeable craftsman who operated machinery. Setups for new product runs are now programmable, made as easy as touching computer screen interfaces that dictate the operations of highly automated machine parts. Lower setup costs involving more flexible production machines facilitate a move toward greater specialization as firms produce smaller batches of products tailor made to the needs of specific customers. The primary point of the model we introduce in this section is that firms that introduce new IT-enabled production equipment are also changing their business strategy – competing less in terms of lowering the production costs of commodity products made in long batch runs, and more in terms of making customized products designed for specific customers that earn higher prices – and this change takes place in part because it becomes much less costly to make switches between products.

To clarify the tradeoffs in the value of new information technology, we model the change in profits that would be expected from falling prices of information technology. Assume that there are two product classes – commodities, "c," that have long batch runs, but lower product market prices, P_c; and specialty products, "s," that have short batch runs, but have higher product prices, P_s:

$$
\begin{aligned}
(1)\quad p = {} & N_cB_cP_c + N_sB_sP_s - [(w + r)(\mathrm{Setup}_c + \mathrm{Runtime}_cB_c + \mathrm{Insp}_cB_c)N_c] \\
& - [(w + r)(\mathrm{Setup}_s + \mathrm{Runtime}_sB_s + \mathrm{Insp}_sB_s)N_s] \\
& - P_{IT}IT - M - a(q_s) + e
\end{aligned}
$$

where $p \equiv$ profits
subscripts $c \equiv$ commodity, $s \equiv$ specialty product
$\mathrm{Setup}_j \equiv$ hours to setup machine to run product; $j = c, s$
$\mathrm{Runtime}_j \equiv$ hours to run each piece of product; $j = c, s$
$\mathrm{Insp}_j \equiv$ hours to inspect each piece of product; $j = c, s$
$B_j \equiv$ average batch size (number produced per scheduled batch) $j = c, s$
$N_j \equiv$ number of batches of product j; $j = c, s$
$a \equiv$ advertising costs (as a function of q_s)
$M \equiv$ materials costs
$e \equiv$ residual
$P_j \equiv$ average price of product j
$w \equiv$ wage rate
$r \equiv$ maintenance cost of capital

$P_{IT} \equiv$ price of new IT capital

$q_s \equiv$ share of output to specialty product $\equiv \dfrac{N_s B_s}{N_s B_s + N_c B_c}$

We can simplify (1) be rewriting it in terms of output, Q, the share of output in specialty products, q_s, and production time T_j:

$$(2)\ \ p = [(1 - q_s) P_c + q_s P_s - (w + r)[T_c (1 - q_s) + T_s q_s]]Q - P_{IT} IT - M - a(q_s) + e$$

where, $Q = N_c B_c + N_s B_s$ and $T_j = \dfrac{\text{Setup}_j}{B_j} + \text{Runtime}_j + \text{Insptime}_j$

Note that operator labor hours per batch equal

$$L_j = (l_1 \text{Setup}_j + l_2 \text{Runtime}_j B_j + l_3 \text{Insp}_j B_j) N_j \ ; \text{for } j = c, s$$

where $l_1 = l_2 = l_3 = 1$ if one person runs each machine, and are otherwise a multiple or fraction of setup and production time.

Assume that production times are a function of IT-imbedded capital and other variables:

$$(3)\qquad \text{Setup}_j = a_{11} IT_j^{Set} + a_{12}(IT_j^{Set} \cdot \text{Specialty}_j) + b_1 X + u_{1j}$$

$$(4)\ \ \text{Runtime}_j = a_{21} IT_j^{R} + b_2 X + u_{2j}$$

$$(5)\qquad \text{Insp}_j = a_{31} IT_j^{I} + b_3 X + u_{3j}$$

where IT_j^{Set}, IT_j^{R}, IT_j^{I} are the IT-imbedded machinery that are used in the setup, running, and inspection of the product, and X are control variables. Let $\text{Specialty}_j = 1$ for specialty products. We posit that $a_{12} < 0$ if setup time is reduced more by IT for specialty products due to the improvements in information technologies aimed at promoting flexibility in machinery use (such as robotics in some production lines).

Given equations (2)-(5), profits will be affected by a fall in the price of IT in the following way

$$(6)\ \ \frac{\partial p}{\partial P_{IT}} = -(w + r)(T_s - T_c)Q\frac{\partial q_s}{\partial P_{IT}} - (w + r)Q q_s \frac{\partial T_s}{\partial P_{IT}} + (P_s - P_c)Q\frac{\partial q_s}{\partial P_{IT}} - IT - a\frac{\partial q_s}{\partial P_{IT}},$$

We examine the effects of falling IT prices on profits. To emphasize the key points, assume that the scale of production, or total output Q, is fixed in the short run.

1. The first term is the decrease in profits due to an increase in time costs if the share of production going to specialty, q_s, rises. The share going to specialty will rise in part if the time costs of production fall more for specialty (where $T_s > T_c$) and the if these increases offset other losses to increased specialty production described below.
2. The second term is the increase in profits from a move to lower setup time from increased IT (holding constant q_s)
3. The third term is the increase in profits from the move to a higher priced specialty product ($P_s > P_c$).
4. The fourth term is the decrease in profits from buying more IT.
5. The fifth term is the decrease in profits from increased marketing costs. If specialty production rises, a bigger increase in q_s will increase advertising costs and other costs associated with finding new customers for the specialty products. These increased advertising costs will tend to limit firms ability to rapidly increase their specialty production.

The model helps identify the costs and benefits of the investments in new IT-aided equipment. It does not identify cases where the benefits measured by the first three terms will outweigh the costs given in terms 4 and 5. However, in a period of dramatic declines in the cost of computing and equally dramatic increases in the capability of computer-aided manufacturing equipment, and with relatively long time horizons to recoup on the capital investment and search costs, one would expect widespread adoption of low cost computer aided production equipment.

H1. Over time, there will be an increase in the adoption of IT-imbedded machinery, which in the valve making industry includes equipment like new CNC machines, new 3D-CAD/CAM design equipment, computerized inspection equipment and others as defined below.

The model also implies the following hypotheses:

H2: IT should promote more product specialization by producers. As long as IT causes larger decreases in T_s than it does in T_c, since setup times will start higher in specialty producers, and the revenue effects outweigh the investment and marketing costs, then adoption of IT equipment associated with lower setup costs will move production towards a larger number of smaller batches, and therefore more specialty production.

H3. Given rising profits from product customization or specialization, plants that survive in the industry over time should be those that are more specialized (or that become more specialized) and those that enter should be more specialized.

H4. IT improves production efficiencies. Setuptime, runtime and inspection time should fall when IT machinery relevant to these processes is adopted. Moreover, it is likely that setuptime time will fall more for specialized products since IT is aimed at improving setup flexibility. This hypothesis is simply a direct test of the assumptions underlying equations (3) – (5).

H5: IT adoption may require new HRM practices and new worker skills. While the role of HRM practices is not considered in the model, a number of studies argue that the adoption of highly automated and technically complex manufacturing equipment may require the adoption of new types of work practices and require new sets of skills from workers.[5] The data collected for this study permit us to examine these further hypotheses that suggest that widespread changes in HRM practices and in the relative wages paid to more skilled workers may in part be due to increased computerization of the workplace.

H6: Value added per input (or total factor productivity) could increase or decrease for more specialized plants:

$$\text{(7)} \qquad \frac{VA}{L} = \frac{\left[(1-q_s)P_c + q_s P_s - M\right]}{L_c + L_s}$$

[5] Milgrom and Roberts (1990) provide a model of "modern manufacturing" that shows that a decrease in the price of all forms of imbedded IT that lower the cost of collecting, organizing and communicating, as well as lowering the cost of flexible design and manufacturing will induce firms to make complementary organizational changes. They acknowledge (p.520) that the greater flexibility in manufacturing is more likely to be correlated with broadly trained workers and greater flexibility of job duties built into the job design and thus with higher levels of teamwork and training.

A drop in P_{it} has an uncertain effect on labor productivity as measured by $\frac{VA}{L}$: a move to greater specialty production $(\uparrow q_s)$ would increase value added unless L_s rises from the move to products with higher levels of setup costs. The change in total factor productivity, or change in value added per input cost, is also uncertain given costs of IT if q_s increases.

Note that the model does not make precise predictions about which specific businesses will find the adoption of new IT profitable. The effect of a business's characteristics on adoption of IT depends on how those characteristics affect all terms in equation (6). Still, the model does help identify factors to be considered. For example, firms that were commodity producers prior to IT adoption may be the ones more likely to adopt IT-based equipment if the revenue effects of the third term in equation (6) are especially large when firms have the opportunity to customize one very large run into an equally large number of one unit batches. Conversely, it could be that plants with customized products prior to adoption will find it profitable to adopt the new equipment since they may already have a large number of customers, so costs of adoption for these kinds of plants are lower than for others. Competitive market conditions may also influence the adoption of IT machinery. Production delays may reduce the demand for the product – perhaps more so in a competitive market than in an oligopolistic market.[6] On the other hand, oligopolistic markets may increase the demand for IT if those markets protect the long run returns to investment. The analysis below will consider the characteristics of adopters to help identify whether estimated effects of IT on operating efficiency and product specialization may be occurring only among certain kinds of businesses.

III. The Valve-Making Industry and Data Description

To study the relationship between IT and HRM inputs and productivity outcomes as concretely as possible, we ground this study in the context of a specific industry – valve manufacturing. To understand the workings of the production process and to identify specific forms of new IT in that process, we visited five valve making plants

[6] This point is emphasized in Milgrom and Roberts (1990), though with an oligopolistic market.

during 1999-2000 and then in 2002 (while designing industry-specific questions during the development of the survey instrument). We also held meetings with a number of plant managers and engineers at the annual meeting of the industry association.

Valve Production Process

To place the empirical analysis into context, a short description of the valve-making we observed during these field visits is useful. A valve is typically a metal device attached to pipes that regulate the flow of liquids or gases – such as the flow of natural gas in a heating system, or the control of liquids in a chemical factory. The central production process in valve making is the machining phase.[7] A simple valve would be made by taking a steel block or pipe and completing several processes on one or more machines; such as, etching grooves at each end for screwing the valve to pipes; boring holes at different spots to attach control devices, and then making and attaching the various devices that control the flow.

Sample

The empirical analysis of this paper analyzes the productivity of this process for a sample of plants in the U.S. valve-making industry (SICs 3491, 3492, 3494, and 3593). We obtained contact information for 762 plants in these industry classes from Survey Sampling, Inc for those establishments with more than 20 employees. 200 of these plants were determined to have no production and another 70 were no longer in business. Assuming a similar rate of survey ineligibility for other plant names that could not be contacted yields a potential universe of 416 valve making plants. 212 plants, or 51%, provided responses to the survey questions described in this section via telephone interviews.[8] Empirical results in the study are based on the responses from these 212 valve-making plants.

Measuring Efficiency in Valve Making

[7] Other processes are welding and assembly of multiple machined parts and final packaging and shipping.

[8] The Office for Survey Research at the Institute for Public Policy and Social Research at Michigan State University conducted the pre-tests and final surveys by telephone from July 31, 2002 through March 30, 2003. Interviews lasted an average of 20 minutes with an average of 7.6 phone contacts need to complete the survey.

Field visits and interviews allowed us to discuss how industry engineers measure operational efficiency. Machining a valve involves *setup* of a machine so the machine will perform the right combination of tasks for the valve's specification, the actual *run* time to complete the machining, and *inspection* to verify the quality of the run. The machining processes required to complete a valve often span several machines, where the number of machines required depends on the technological capabilities of the machines. We measure these three components of overall machining efficiency with the following survey questions that ask the respondent to give answers about "the product you have produced the most over the last five years:

<u>Setup Time</u>*: About how much setup time does (did) it take to produce this product today (and in 1997)?*

<u>Inspection Time</u>*: About how long does (did) it take to inspect one unit of this product today (and in 1997)?*

<u>Run Time</u>*: About how much run time does (did) it take to produce this product today (and in 1997)?*

We focus on these time-based efficiency questions since plant visits indicated the importance of accounting for product heterogeneity – no two valves products are ever exactly alike. The complexity of a given valve and the number of different milling, grading, etching, boring, and other machining processes increase with product complexity and thus increase setup, run and inspection times. Moreover, data on complexity or the number of detailed machining processes involved in a given run are not kept or easily reported by plants. For these reasons, we therefore concentrate on the within-product changes in the time-based measures of efficiency between 1997 and 2002 as our most useful measures of efficiency.

Measures of the time it takes to complete different production stages allow us to identify any process improvements in valve making. Productivity may also increase because plants can make more customized valves, tailor-made more precisely to customer needs. To measure the extent of product customization, we ask respondents to identify the batch size for its main product.

Batch Size: *What was the typical batch size for the plant's main valve product in 2002 (1997).*

As described in Hypothesis H2, a reduction in batch size over the five-year period is taken as an indicator of increased customization of the main product as well as more frequent filling of new orders. This is a lower bound measure of the returns to customization, because presumably increasing abilities to customize valve products would reveal itself through a larger product variety, which is therefore not specific to one product.

Measuring Computer-Based IT in Valve Making

In the past, the reshaping of the steel pipe or block would be done on a work bench by a highly skilled machinist using manual tools. Today, much of valve making is highly automated due to the integration of IT and other computer-based technologies into valve making equipment. The central piece of equipment in the valve making production process is a CNC (Computer Numerically Controlled) machine that lines up the block on the pallet of the machine and automatically drills and chips in the proper places based on directions entered into the machine's operating software.[9] CNC machines are now in widespread use in the industry.

During our site visits and interviews, managers routinely identified as important sources of improved operational efficiency one or more of the following three specific technologies – advances in the capabilities of the CNC machines themselves; flexible manufacturing systems (FMS) that coordinate the operations of multiple machines; and new automated valve inspection equipment. All three technological advances are a direct result of improvements in advances in the capability of microprocessor, storage, and software computer technologies.

Increases in computing power improved the capabilities of CNC machines considerably. Operators can now program a modern CNC machine more easily through

[9] CNC machines were predated by numerically controlled (NC) machines in which fixed computer programs for a given run, originally input on tape, controlled the action of machines during that run. Manual, NC, and CNC machines of different vintages all still exist in the industry, but sophisticated CNC are now dominant.

much simpler software interfaces, and each machine can now perform a much wider variety of tasks on the block of steel. During plant visits we made to valve manufacturers, we were shown evidence that increasing CNC sophistication results directly in a decrease in the number of machines needed to produce a given product. For example, in 1980 a typical product at one plant would be produced on about seven machines; by 2002 that same product would be made on two CNC machines. This evidence indicates that investing in newer CNC machines often reduces the total number of machines needed to machine a valve. The move to a smaller number of more advanced machines to produce a given product leads to significant reductions in setup time (fewer machines to set up and each is easier to program).

A second technology, flexible manufacturing systems, coordinates machining operations across different CNC machines. To complete all the machining tasks for a given valve, it is much more common for multiple machines to be involved than for only one to be involved, and this is especially true for more complex valves. FMS is an IT process in which software automates the coordination of the production tasks for a given run of valves across different machines. FMS technology speeds up the run time for a given valve product.

Finally, plant tours and interviews identified new IT-based advances that have reduced the time it takes to inspect valves in the quality control process. Each dimension of a complicated valve often must be produced to an accuracy rate of 1/1000 of an inch, so inspection is a critical part of the production process. For many years, inspection was done with hand-measuring devices, which was very time-consuming. In the last few years, inspection machines have been introduced which use a laser probe technology, so that the operator touches each surface (interior, exterior, holes, etc.) of the valve with a probe that develops a three-dimensional picture and measures all dimensions and automatically compares measurements to the desired product specifications.

Another technology that is becoming more common in valve making plants is three-dimensional computer-aided-design (3D-CAD). This is a constantly advancing IT method for turning customers' valve specifications into a specific design. According to interviews, this technology impacts the design phase and so the presence of this technology is not expected to affect setup, run, or inspection times in the machining stage.

The survey asks for information on the adoption of each of these IT-aided technologies that managers indicated were important determinants of the efficiency of valve making:

Number of Machines: How many machines it takes to make the plant's main product in 2002 (1997).

Flexible Manufacturing Systems (FMS): Does the plant have FMS technology and what was the year of adoption.

Automatic Valve Inspection Sensors: Does the plant have automated inspection sensor equipment and what was the year of adoption.

Three Dimensional CADCAM design equipment: Does the plant have three-dimensional CADCAM technology and what was the year of adoption.

Importantly, these specific pieces of IT-enabled production equipment affect specific production stages. When plants use fewer machines to produce a product, the amount of setup declines because there are fewer machines to set up, and the runtime should decrease as well, but by a smaller percentage. FMS technologies coordinate the operations of machines during product runs, and the IT-sensors automate the inspection stage of production. CADCAM technologies affect valve designing and would only have indirect effects on production stages if design changes affect production but otherwise are not directly involved in the direct manufacturing steps.

Measuring HRM Practices and Worker Skills in Valve-Making Plants

While direct tests of the productivity effects of specific IT-based technologies are few, the existing literature on the relationship of new IT production technologies and productivity also suggests that new technologies may be related to an increased demand for more skilled workers. New technologies may require some combination of higher skill levels and possibly a different mix of skills, with a greater focus on cognitive problem-solving skills as IT reduces the need for operators to do mechanically setup the machines or monitor them, and thus operators are more involved in solving operating problems that arise from day-to-day changes or from increased new products in production (Autor, Levy and Murnane, 2003).

We collect data in our valve industry survey to measure whether plants tried to increase worker skills through a training program in basic math and reading skills or through training in new technical skills for operating new technologies. Other survey questions ask about the use of HRM practices besides training programs, such as problem solving teams, and what year each practice was first introduced. In models that estimate the improvement in machining efficiency between 1997 and 2002, we would expect that the introduction of training between 1997 and 2002 would improve efficiency if higher levels of those particular skills were important.

In the analysis below, we complement data from our valve industry survey with data from two other sources. First, we also utilize data on valve making plants from the Census Bureau's Longitudinal Research Database. To date, only data through 1997 are available and so we examine data for the 1997 cross-section of plants, while longitudinal analyses using the LRD will span the 1992-1997 period. Second, one valve making plant that we visited provided detailed production data for all the product varieties that it produces. Much of the analysis using the valve survey concerns the production of the plant's main product. With the plant-specific data, we can examine production of a much wider range of products.

IV. Trends in Productivity, IT Investments and Work Organization in the Valve-Making Industry

The principal motivation for this study is to study the relationships between new IT investments, new methods of work organization and worker skills, and productivity improvements in terms of both process and product improvements in the context of the specific setting of one industry's production process. Before turning to the regression results that examine the relationships between specific pieces of IT equipment and the productivity and specialization of the plants, we want to examine the time series evidence on changes in the use and performance of IT-machinery and HR and trends in specialization.

Hypothesis H1 makes the straightforward prediction that, with dramatic declines in the cost of computing, plants will increasingly adopt new IT-aided equipment. Table 1 in Panel A examines the time path of adoption for three types of IT equipment for which the survey asks the year of adoption. All three show large increases in usage since 1980. The highest rates of adoption for the first CNC machines occurred during the 1980's while the other two technologies show the largest growth after 1995.[10]

The survey also asks for the year of adoption for certain HRM practices, and panel B of Table 1 reports the time path of adoption for these practices. The patterns in the panel offer suggestive evidence in favor of hypothesis 5 that new technologies may also require new HRM practices. The use of teams, training programs and incentive pay plans all increased since 1980 with the highest rates of adoption of these practices occurring after 1990.

The valve industry survey also asks for information on a wider range of variables measuring productivity, IT equipment, and HRM practices for 1997 and 2002. According to Table 2, trends in the valve-making industry mirror those in the larger U.S. economy, as valve making industry shows improvements in process and product innovation over this period, as well as an increasing reliance on new IT production technologies and new HRM practices. Lines 1-3 reveal that, on average, plants realized large declines in production times for making their most common product in each of the three production stages. The largest declines came in the setup stage. These improvements in process efficiency coincided with greater customization of the main product as batch sizes for the main product declined at the same time that production times per valve were declining (line 5).

All four computer-aided technologies became increasingly common over the 1997 to 2002 period as well. Line 6 in panel A reveals that, as a result of technological advances in capabilities of CNC machines, on average it took 19 percent fewer machines to produce a given valve product in 2002 compared to 1997. According to the figures in lines 1-3 of panel B, FMS technology, automated inspection sensors, and 3D-CAD technology were adopted by an additional 15%, 14%, and 39% of our sample of valve making establishments between 1997 and 2002. Finally, valve plants increasingly adopted new training programs and more team-based methods of job design (panel B,

[10] The first CNC machines were purchased more in the 1980s, but in our empirical work below we focus on the adoption of new-vintage CNC machines, not the first machines.

lines 3-6). Basic training programs in reading in math skills, technical skills training, and teams were adopted by 12%, 21%, and 30%, respectively, between 1997 and 2002.

The patterns in the summary statistics in Table 2 show that all three dimensions of machining time declined over the same time period that new computer-enabled production technologies and new HRM practices became increasingly common. At the same time, different plants adopted different pieces and combinations of IT equipment and HRM practices. It is not the case that some plants adopted all of the technologies and practices while others adopted none. The empirical work on the efficiency effects of new IT-based production technologies and new HRM practices therefore allows for a particularly powerful test of these new technology and organizational investments. In particular, the models to follow will examine whether the improvements in various aspects of machining times over this period are concentrated in those plants that have made investments in these technological improvements. Moreover, the models will test whether specific pieces of equipment that impact only individual stages of production (e.g., automated inspection equipment and the inspection stage) affect the specific stage of production in which it is located.

V. Specialization in the Valve-Making Industry and the Role of IT

According to Hypothesis H2, new information technology should promote greater product specialization, since new IT equipment should make it less costly to switch between product varieties and allow producers to customize features of valves for different customers. In Table 3, we examine whether plants that adopt new IT equipment produce their main product in smaller batches. This is a rigorous test of the customization hypothesis since the data here pertain to the batch size of the plant's main valve product. The empirical test here therefore examines whether the plant is producing a larger number of tailor-made batches of the main product after new IT equipment is introduced.

The results in Table 3 show that batch size falls with the use of more flexible IT machinery. When plants reduce the number of machines used to make the main product, batch sizes also go down. A smaller number of more powerful CNC machines allows the plant to produce smaller batches of its main product as a way of meeting more specific needs of customers for this product or as a reflection of the overall increase in specialty production. The results show that it is a specific type of IT equipment that permits this move to smaller batches – the use of a smaller number of more sophisticated CNC machines – and this machinery is exactly the technology that managers described as being most responsible for savings in setup time.

Table 4 examines a different dimension of specialization in the industry. Industrial organization studies typically identify increasing specialization within an industry by demonstrating an increase in the Primary Product Specialization Ratio (PPSR). The PPSR is the fraction of plant output accounted for by the plant's primary seven-digit SIC product. Increases in the PPSR therefore demonstrate that plants in the industry are specializing in specific 7-digit products. We use the Census Bureau's Longitudinal Research Database which reports data on PPSR to examine changes in this measure of specialization in the valve industry.

It is important to note that increasing PPSR within plants in an industry is still consistent with the move to smaller batches within plants. There is still considerable customization and variety within 7-digit product categories. To demonstrate this point, we create a matched sample of survey plants (that report batch size of the main product for 1997) and LRD plants (that report the PPSR for 1997) and calculate the correlation between batch size in 1997 and PPSR in 1997. The two measures are negatively correlated at the 1% significance level. Plants that focus to a greater degree on a small number of 7-digit valve products classes are the same plants that produce in smaller batches.

Table 4 therefore examines this second aspect of product specialization – a move toward having plants specializing in the production of fewer 7-digit product categories – by examining whether valve plants in the Longitudinal Research Database that are more specialized are less likely to exit the industry or more likely to enter and thus infer that specialized plants may be more profitable. According to Hypothesis H3, given rising profits from product customization, plants that survive in the industry over time should be those that produce more customized or specialized products and those that enter should produce customized/specialized products.

We use the LRD data to study both entry and exit patterns in the valve industry during the time period 1992-1997. First, to investigate the relationship between PPSR and entry into the valve industry, we estimated a probit regression on the sample of plants in existence in 1997; the dependent variable equals one if the plants was not in existence in 1992. The independent variables are PPSR in 1997, Value-Added, and Capital Intensity. The results from different specifications of this industry entry equation in columns (1) – (3) in Table 4 all indicate that new plants have significantly higher values of PPSR than the older plants.

Next, to identify what types of plants are exiting the industry, we identified those plants that were in existence in 1992 and then determined whether they were no longer in operation in 1997. We estimated a probit equation (dependent variable Exit =1) in which the independent variables are PPSR in 1992, a dummy for Large plant (equals one if plant is in top quartile of size distribution), the interaction of PPSR and Large, Age of plant, Value-Added, and Capital Intensity. The results are shown in columns (4)- (6) of Table 4. Here, plants that were specializing in fewer 7-digit products are in fact more likely to exit the industry by 1997, but this pattern only exists among bigger plants. PPSR has no effect on plant closing probabilities among the smallest valve plants. Table 4 thus documents that like other U.S. manufacturing industries, the composition of the U.S. valve-making industry has been shifting towards plants that are specializing in a narrower range of 7-digit product classes. Table 3 notes that, within this industry that exhibits a narrowing of the number of 7-digit products within specific plants, those plants that invest in certain IT equipment are customizing features of their main products to a greater degree over time.

VI. Conventional Productivity Estimates Using LRD Plant-Level Data

Instead of conducting a series of plant visits to understand production in a given industry and then collecting productivity and technology data through a survey tailored to that industry, an alternative, and more common, approach for investigating organization-level determinants of productivity would be to use pre-existing sources of plant-level data and possibly augmenting these data with some specific variable of interest. Yet, long experience with trying to identify causes of new trends in productivity have led to the observation that "standard census type data do not provide enough additional information or relevant product and plant characteristics to allow one to pursue a substantive analysis." (Griliches and Mairesse, 1995, pp. 23-4) To contrast results from our empirical analysis based on a industry-specific survey with what can be determined from existing census data sources, we introduce the empirical analysis by first estimating standard models of the effects of capital and worker skills on productivity using one common source of plant-level data, the LRD data base from the Census of Manufactures. We will then compare results from these models to results obtained when productivity models are estimated using data from the survey tailor-made for the details of valve makers' production process.

With only a very small number of possible measures for plant output and for capital and labor inputs, a standard starting point for analyses with these data would be to estimate a simple functional form for a production function, such as:

(8) $\ln Q = a + b_1 * \ln K + b_2 * \ln L + b_3 * \ln M + e_1$

Where Q, K, L, and M are respectively the natural logarithms of output, capital input, labor input, and materials input so that (8) is just the ln-transformation of the Cobb-Douglas specification. Standard measures used from the LRD surveys are total value of shipments, gross value of depreciable assets, labor hours and cost of materials. If additional data on worker skills through education measures or through organizations' work practices such as teams or training programs (HR), then L in equation (8) can be modeled as some proportion of the reported labor input (RL) where the proportion varies with variables like an HR change according to:

(9) $L = RL(1+dHR)$, so that

(10) $\ln Q = a + b_4 * \ln K + b_5 * \ln RL + b_6 * \ln M + b_7 * HR + e2$

While other functional forms can be estimated, the variables used to measure inputs and output are limited by the available survey data.

We identified the plants in the LRD for 1997 and 1992 that match the sample of plants in our own survey using address and name matches.[11] We estimate (8) with the 1997 LRD data for this sample of plants (n=178). We then estimate (10) using the same data but including our own survey's measure for the presence of three HRM practices: a basic training program, a training program in new technical skills, and the presence of

[11] Our use of the Longitudinal Research Database for this project has been approved by the Census Bureau.

problem-solving teams. Finally, equations (9) and (10) are re-estimated in first-difference form for the 1992-1997 time period. The results are shown in Table 5 where we observe that labor and materials inputs are significant in both the OLS and first-difference specifications.

The insignificance of the capital input is similar to what others have observed even when using the full sample of plants in the LRD (Black and Lynch, 2001) and is generally attributed to measurement error (e.g. if plant and property expenditures are important parts of the capital variable but relatively uncorrelated with output variation) or endogeneity bias. We are able to deal with the measurement error problem by using a direct measure from our own industry-specific survey – namely the number of CNC machines that the plant had in place in 1997. This is a more appropriate measure of capital for this industry because it identifies the actual number of machines that are a fundamental part of the production process. When we replace the LRD capital measure with this measure, we find a positive and significant coefficient in the levels equation (see column (2)). Finally, when we include the three HR measures in the equation, we find a positive and significant effect of the presence of problem-solving teams, but not training, in the first-difference specification.[12] In sum, the data that are traditionally available in the plant-level data sets do not lend themselves to identifying labor-productivity gains.

VII. Estimates of the Determinants of Productivity at the Product Level

This section focuses on the following first difference productivity models in which our time-based efficiency measures are expressed as a function of the adoption of new machining technologies and new training practices.

$$(11)\ \ln(\text{Time02} / \text{Time97}) = a + b_1(\text{newtech97,02}) + b_2(\text{newhrm97,02}) + b_3(X) + e_1$$

[12] Finally, we posit that greater specialization could be correlated with increases in value added per person (Hypothesis 8). In value added regressions comparable to those in Table 3, we find no effect of PPSR on value added or changes in value added. This lack of correlation may reflect omitted variable problems (such as omitting costs of marketing or new capital).

The dependent variable in (11) measures the change in a given machining time between 1997 and 2002 – the changes in setup time, run time and inspection time. The vector newtech97,02 measures the adoption of new technologies expected to reduce these machining times – the adoption of fms, automated inspection, and 3D CAD technologies, as well as the change in the number of machines needed to produce the plant's main product. The vector newhrm97,02 measures the adoption of new HRM practices, such as work teams and training programs since 1997, and X is a vector of controls including the age of the plant, union status, and plant size measured as number of workers to test whether the change in machining efficiency is affected by these additional factors.

<u>Estimates of the Effects of Specific Valve-Making Technologies on Machining Times</u>

Hypothesis 4 states that IT equipment will improve operating efficiencies of the various stages. Consistent with this hypothesis, the results in Table 6 demonstrate that investments in new IT-machinery have improved 'process efficiency' by reducing all components of production times. The dependent variables are the change in setup time, run time, and inspection time. The results are remarkably straightforward and striking: the adoption of new technologies into a given stage of the machining process reduces production times in that stage significantly. Using fewer machines reduces setup times (column 1). Run time also declines with the use of fewer machines, but less significantly, and runtime declines significantly in plants that adopt FMS technology (column 3). Inspection time declines with the introduction of new automated inspection equipment (column 4).

The first pattern in Table 6 can be summarized simply. *New IT-based production machinery improves the efficiency of the stage of production in which it is involved. New computer technologies do not improve the efficiency of phases of machining in which they are not involved.* These results stand in sharp contrast to results obtained with plant-level LRD data using similar OLS estimation methods that find that the partial correlation of capital and sales is insignificantly different from zero, and the change in capital is uncorrelated with the change in sales for exactly the same set of plants used in Table 6.

The theoretical discussion of section II draws special attention to reductions in setup time. There, we argued that the move toward greater customization and smaller batch sizes after new IT equipment is installed (documented in Table 3) occurs because of reductions in setup time that the new IT will produce. Specifically, if IT equipment reduces setup times, it is less costly for plants to make switches in production runs. In column 1 of Table 6, the results show that the measure of IT that reduces setup times – the use of a smaller number of more sophisticated CNC machines (line 1) – is precisely the same IT measure that promotes the movement to smaller batches in these plants. Certain IT investments reduce setup times, and, when plants make these specific types of investments, they are able to move to greater customization of their main valve products.

The column 2 model investigates the effects of this IT measure on setup times in more detail. In particular, Hypothesis 4 makes the more specific prediction that specialty producers are more likely to gain from CNC-based IT investments. The column 2 model expands the column 1 specification by adding two variables to measure the effects of batch size and the interaction of batch size and the change-in-machines variable. The results in column 2 show that plants with small batch size (measured as 1/BATCH) reduce setup time more if the plant has also reduced the number of CNC machines it uses. The effect is nonlinear – the incremental gains to the use of a smaller number of more sophisticated CNC machines is greater for small batches than large batches. Specialty producers gain the most from IT investments.

These savings in setup times are important. The means on production times reported in Table 2 show that setup times in 1997 were the largest component of overall production time, accounting for almost one-half of overall production time. Furthermore, the reduction in setup times due to the IT variable that measures a reduction in the number of CNC machines implies a large reduction in setup times. Evaluating the magnitude of the drop in setup times due to a reduction of two CNC machines (or .439 ln-units, which corresponds to the mean decrease in machines for plants that did experience a decrease in the number of machines after 1997), we calculate that this decrease in machines led to a decline in setup time for one unit of 3.45 hours. This IT investment therefore accounts for a large part of the observed reduction in setup times between 1997 and 2002. Plants that made these specific types of IT investments also began producing smaller batches of more customized products.

Estimating the Productivity Gains from IT Using Detailed Data from One Plant

In the previous section, we provided evidence from our survey data that new information technology has led to significant increases in productivity in the valve-making industry. In this section, we provide similar evidence from a dataset that is even more detailed than our survey data. Specifically, one of the plants in our sample provided us with data on setup time and run time for each of the approximately 330 detailed products that they produced during the late 1990s along with information on the number of machines used to produce each of these products. Since we have this detailed product-level data for at least two years for each product (total number of observations is 790), we are able to estimate within-product productivity equations. Thus we are able to estimate the effect of new IT on the production time of a large group of randomly chosen products:

?Setup	= .551 (?#of machines) (.0345)	R^2 = .44
?Runtime	= .0767 (?#of machines) (.0262)	R^2 = .17

Using fewer machines to produce a given product reduces both setup time and run time.

<u>Changes in the Effectiveness and Demand for Operators' Skills</u>

Hypothesis 5 suggests that new IT investments may also require new sets of worker skills and new HRM practices. In Table 7, we replicate the Table 6 production time regressions but also introduce variables measuring the adoption of certain HRM practices between 1997 and 2002. According to the results in Table 7, plants that introduce technical training programs also realize an additional reduction in setup and run times. (Hypothesis H4). These efficiency regressions find no apparent effects of other HR practices such as teams or basic training. However, it is important to remember that we are modeling the efficiency gains over time for one specific product, not the overall efficiency of the plant. Teams may be less likely to have a direct effect on product efficiency as compared to overall plant efficiency. The results in Table 7 support a conclusion that *initiatives designed to improve the specific skills needed to operate new technologies in the plant are in fact the initiatives that improve operational efficiency.*

The relevant follow-up question is, does the introduction of new product-level IT machinery increase skill demand? The introduction of product-level IT is significantly correlated with an increase in the demand for computer skills to run the machines (Table 8, column 2), but no other broader skills such as problem solving (column 4) or specific skills such as math, programming or cutting tool knowledge. We suspect that the IT machinery may substitute for some of these other skills such as cutting and machining skills (our plant visits report that the specific skills are still required, but not increased). Interviews during plant visits indicated that the use of teamwork (and not IT investments themselves) made problem-solving skills more important. Consistent with this claim, an increase in the importance of problem-solving skills is correlated with the introduction of teams (correlation = 0.14, significant at 5% level), but teams were also fairly widespread prior to 1997 (35% had teams).

VIII. Assessing Potential Bias in Estimated Productivity Effects of IT and HRM Practices

The preceding empirical analysis reports a series of simple first-difference models of the determinants of improvements in production times and reductions in batch sizes between 1997 and 2002. Using very detailed industry-specific measures of IT production equipment and plant-specific HRM practices, we find that new IT equipment improves the operational efficiency of the production stages in which it operates, while new technical training programs have their own independent effect on setup and run times. Since these pieces of equipment and HRM practices are not universally adopted, the question naturally arises as to whether the estimated improvements in manufacturing times or product customization would actually be enjoyed by those plants that have yet to adopt the new technologies. That is, is the reason behind the non-adoption of new IT and new HRM practices in some plants the fact the non-adopters would not experience the same improvements in efficiency?

First, with regard to the possibility of endogeneity bias, the rich detailed data that allow us to study improvements in the efficiency of specific machines limit the persuasiveness of this interpretation. Consider, for example, the setup time regression. The only way that setup time can be reduced over time for the same product is if the technology has changed, either because workers are better able to use the existing technology (perhaps due to better training) or because there is new technology. Based on plant visits and our understanding of the production function, there is no reason for a decline in setup time to *cause* a decline in the number of machines in use. Moreover, our data does not include short term shocks to production (such as machine failures) that could be correlated with changes in input use – we have typical times, not today's times. Thus, some endogeneity problems are avoided with these data.

Two potential problems remain. First, there may be some omitted variable bias in our results, if, for example, a reduction in the number of machines used to produce a given product is correlated with unobserved contemporaneous changes in the organization (such as managerial skills). Here, the narrow scope of the productivity model (spanning the operations of only a few machines) limits this problem and direct contact with the plants and their managers allow the researcher to investigate whether such confounding factors exist. Furthermore, because some pieces of equipment improve efficiency (those in that stage of production) while others do not (those not in that stage of production), an omitted variable that is simply correlated with IT is not a specific enough factor to explain the results shown in Tables 6 and 7 above. One would need to identify a series of omitted variables with different omitted variables correlated with the different pieces of equipment in different stages.

Second, there may be selectivity bias. Adopters of new technologies (like new CNC machines that reduce the number of machines per product produced) may be the plants that have the most to gain from the new technologies. Non-adopters are either dropping out of our sample if they go out of business, or may not earn the same returns to technological change as the adopters do. Again, the machine-level of analysis we pursue in this study should be considered for assessing a particular version of this selectivity argument. Once a new valve making machine is put in place, the idea that those machines would be selectively used for easier-to-manufacture products that have quicker setup times does not make sense in this industry. The argument cuts the other way. The new valve making machines are used to produce harder-to-make products, yet setup times go down in plants where they are introduced. The simple productivity models we estimate measure the correlation between the introduction of a given technology on speed of a production phase for a given product, and if anything, that product becomes more complicated after the introduction of new machines.[13]

If bias in the estimated coefficients on the IT variables in the production time equations is not an important concern in these data and models, what factors might explain why some firms in the valve-making industry do not adopt new time-saving IT equipment? The model of section II states simply that adoption occurs in plants where the revenue effects associated with terms 2 and 3 in equation (6) outweigh the costs given by terms 1, 4 and 5. Our survey data do not include a profit measure since managers in pre-tests routinely would not divulge this information. Our analysis instead measures efficiency gains the way industry engineers do – in terms of reductions in production times. The most reasonable and obvious explanation for why some plants have not adopted these time-saving technologies is that some plants do not value the time savings as much as others. Some possibilities here are that some plants may have more down time in their production schedules than others, and some plants may have customers who do not need their orders filled as quickly as others. Here, the new technologies would reduce production times. High technology inspection equipment would reduce inspection times. However, for some plants these reductions in production times would not lead to an increase in profits.

In Table 9, we report empirical patterns about the plants that do and do not adopt new IT equipment. We pay particular attention to the possibility that plants that operate in more (less) competitive markets may be more (less) likely to invest in the time-saving IT equipment. In panel A of Table 9, the dependent variable is a dummy which equals one if the plant invested in a new CNC machine between 1997 and 2002. In Panel B, the dependent variable is a dummy which equals one if the plants invested in any one of three types of new IT equipment between 1997 and 2002 – a new CNC machine, flexible manufacturing systems, or automated inspection sensors.

We investigate the effects of market power on adoption by defining four market types in which the valve producers can operate. Based on answers to survey questions

[13] There are also concerns that estimates of the overall productivity effects of these new IT-based production technologies are understated. By focusing on the efficiency of producing one product, we miss changes in product mix that may well contribute to the returns to the adoption of new technologies.

asking respondents the number of competitors, and the percent of product that is sold to the top four customers, the four market categories are:

HiCompHiConc: high number of competitors (above the median of 6) and highly concentrated (so that the top four customers of plant account for more than 45% of revenue, which is the median value for percent of product going to top four customers)

HiCompLoConc: high number of competitors and not highly concentrated (less than 45% of revenue goes to top 4 customers).

LoCompHiConc: low number of competitors and highly concentrated.

LoCompLoConc: low number of competitors and not highly concentrated.

The profitability of adoption may also differ between plants that start the 1997 period as specialty producers and those that were commodity producers at the start of the period. In order to measure the extent of product specialization for the overall plant (in contrast to product-specific measure of customization, *batch size*), we create the plant-level variable *specialty* which equals one if the valve producer indicated that less than 90% of its output goes to filling catalog orders. Producers who use at least 90% of their output to fill catalog orders are called "commodity producers." For the two groups, "specialty producers" and "commodity producers," 40% and 92% of their average output goes to filling catalog orders. Approximately 60% of the plants in our sample are specialty producers and 40% of the plants are commodity producers. In some specifications, we interact the variable *Specialty* with a dummy variable *Big* which equals one if the plant has at least 50 employees.

With regard to the effects of the market type variables, the results in Table 9 show plants that are competing with a large number of other competitors (HiComp), regardless of the level of concentration in the buyers market (either LoConc or HiConc), are significantly more likely to adopt new IT equipment. In both panels A and B, coefficients on HiComp variables in lines 1 and 2 are significant and positive in all specifications. One interpretation of these results is that plants that enjoy a high degree of product market power already charge monopoly prices for their valve products and would not realize further increases in the price of their valves if they invested in IT equipment that made it easier to produce more specialized products. Other results in

Table 9 reveal that plants that have higher levels of product specialization in 1997 are more likely to invest in the newest vintage CNC machines and other IT equipment. As is typical in the capital investment literature, big firms are more likely to invest in IT (column 2). However, when we interact big with the degree of product specialization, we find that it is big firms that are producing specialized products that invest in IT – just being big does not increase investment.[14]

In sum, we expect that the adoption of more sophisticated CNC machines, FMS technology, or new automated inspection equipment would improve production times for all plants. However, for some plants such as those with more product market power that may already be charging monopolistic prices for their valves, it would not be profitable to invest in equipment that reduced production times.

IX. Conclusion

During the latter half of the 1990's, the rate of investment in computers and software grew at an extraordinary rate of 28% per year. Many analysts point to the widespread adoption of new computer aided information technologies (IT) as an important cause for the rapid rates of productivity growth experienced by the U.S. in the last decade, as well as for many other trends over this period that have dramatically reshaped the U.S. economy including widespread changes in the organization of work and an increasing demand for new kinds of employee skills. Much of the existing research is based on aggregate data that examines the timing of IT investments and the timing of productivity changes for the economy or for broad industry groupings. Firm-level research is less common and analysis here is often based on cross-industry surveys, forcing analysts to examine general measures of IT that may have very different effects in different industrial settings. Missing from the existing empirical literature on the effects of IT on productivity, work organization and worker skills are studies that identify what IT really means in the context of specific production processes with tests of the effects of new IT investments on the efficiency and organization of those production processes.

[14] We also find that there are adjustment costs in introducing new CNC machines. Plants with high levels of CNC in 1997 are more likely to purchase new CNC, all else constant

This paper fills this gap in the literature by conducting an in-depth study of the determinants of productivity in a specific manufacturing production process – valve making. The central argument we test is that the adoption of new IT changes the business strategy of the production unit. Adopting new IT will itself change how a company competes. New IT embodies a shift away from strategies that emphasize being a low cost producer of a standardized product toward strategies that emphasize being a higher revenue producer that makes more customized products that meet specific needs of different customers Using personally collected longitudinal data on specific IT investments, productivity measures, work practices, and worker skills for plants in the valve-making industry, we investigate the effects of the adoption of new IT on product specialization, as well as the effects of IT on the specific aspect of operations that permits this shift in strategy – that is, changes in the time it takes to switch production from one product variety to another. Finally, the paper examines whether IT adoption is accompanied by a change in work practices inside the plant or in the worker skills needed when new machinery is adopted.

The empirical findings of the paper reveal a complex web of changes that occurs as manufacturers adopt new IT-aided production equipment. New IT changes how the firm competes and expands the range of product varieties it produces. New IT allows this because of gains in operational efficiency, especially the efficiency of switching production operations over from one product variety to another. Finally, the adoption of new computer-aided production technologies also changes worker skills and new HRM practices as well. The adoption of new IT machinery entails much more than the installation of new equipment on the factory floor.

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Table 1

The Diffusion of New Technologies and New HRM Practices in the U.S. Valve Industry

Panel A: Percent of Plants with Computer-Aided Production Technologies

Year	First CNC Machine	Computerized Product Inspection	3-D CAD/CAM Design
1980	.25	.01	.01
1985	.48	.03	.02
1990	.66	.10	.09
1995	.78	.13	.24
2000	.86	.25	.63
2002	.87	.28	.73

Panel B: Percent of Plants with New HRM Practices

Year	Teams	Training	Any Incentive Pay
1980	.03	.17	.10
1985	.06	.21	.16
1990	.14	.29	.21
1995	.34	.50	.26
2000	.58	.72	.45
2002	.63	.75	.50

Table 2
Summary Statistics on Production Times in Valve Machining, New Computer-Based Production Technologies, and HRM Practices

Panel A: Product-Level Variables	***Mean Value for 1997***[1]	***Mean Value for 2002***[2]	***Log change between 1997 and 2002***
Setup time	0.49	0.28	-0.681
Run time	0.45	0.39	-0.371
Inspection time	0.05	0.03	-0.334
Total time	1.03	0.72	-0.481
Batch Size	3152	2870	-0.646
Number of machines	5.63	4.97	-0.189

Panel B: Plant-Level Variables	***Fraction of obs. using equipment or HRM practices in 2002***	***Fraction of obs. adopting equipment or HRM practices bet. 1997 and 2002***
FMS	0.337	0.151
Auto sensors	0.283	0.137
3d Cad	0.738	0.387
Basic training	0.333	0.119
Technical training	0.726	0.211
Teams	0.647	0.298

1. In fractions of a day except for Number of machines.

2. In fractions of a day except for Number of machines.

Table 3

The Effects of IT on Batch Size[a]
First Difference Regressions

	Change in Batch Size 97-02
Percentage Change in Machines 97-02	0.750 (0.244)***
Introduced Flexible Manufacturing 97-02	0.097 (0.283)
Introduced Automatic Sensors 97-02	0.168 (0.359)
Introduced Computer Aided Design 97-02	0.216 (0.232)
Observations	117
R-squared	0.16

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
a All regressions include controls for age of plants, number of shopfloor workers and dummy for unionization

Table 4
Determinants of Entry and Exit in the Valve Industry Between 1992 and 1997 [a]

	ENTRY			EXIT		
	(1)	(2)	(3)	(4)	(5)	(6)
PPSR	0.0011* (0.0006)	0.0011* (0.0006)	0.0011* (0.0006)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)
Big						
Employment >= 50	-0.165*** (0.024)			0.094 (0.120)		
Employment > 77		-0.181** (0.023)			0.168 (0.142)	
Employment > 100			-0.165 (0.025)			0.235 (0.167)
PPSR*Big				-0.002* (0.001)	-0.003** (0.001)	-0.004** (0.002)
Age						
Less than 5 years				0.175*** (0.032)	0.181*** (0.032)	0.186*** (0.032)
Less than 10 years				0.075** (0.037)	0.083** (0.037)	0.085** (0.037)
Less than 15 years				0.043 (0.036)	0.040 (0.036)	0.045 (0.036)
Value Added	-0.000001 (0.0000009)	-0.000001 (0.0000008)	-0.000006 (0.0000009)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
Capital Intensity	-0.0003 (0.0004)	-0.0002 (0.0004)	-0.0003 (0.0004)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
N	1529	1529	1529	1424	1424	1424
Pseudo R^2	0.047	0.056	0.047	0.061	.059	0.059

[a] Probit coefficients (evaluated at the mean) and standard errors in parentheses.
* - Significant at 10% level; ** - significant at 5% level; *** - significant at 1% level.

Table 5
LRD Productivity Regressions[a]

Independent Variable	(1) 1997 Levels	(2) 1997 Levels	(3) 1997 Levels	(4) 1992 -1997 First Differences	(5) 1992 -1997 First Differences	(6) 1992-1997 First Differences
Log (total hours)	0.384*** (0.040)	0.394*** (0.039)	0.384*** (0.04)	0.219*** (0.041)	0.260*** (0.046)	0.215*** (0.04)
Log (Capital)	-0.010 (-0.41)	———	-0.009 (0.024)	-0.015 (0.26)	———	-0.006 (0.026)
Log (CNC Machines)	———	0.052** (0.02)	———	———	-0.002 (0.023)	———
Log (Materials)	0.610*** (0.035)	0.585*** (0.032)	0.609*** (0.035)	0.516*** (0.036)	0.475*** (0.035)	0.509*** (0.036)
Basic Training	———	———	-0.025 (0.063)	———	———	-0.000 (0.00)
Technical Training	———	———	-0.011 (0.049)	———	———	0.070 (0.06)
Teams	———	———	0.046 (0.050)	———	———	0.104* (0.06)
Number of Observations	178	167	178	145	143	145
R^2	0.938	0.940	0.939	0.721	0.691	0.731

[a] The sample comprises plants in the authors' survey.
Standard errors are in parentheses
***Statistically significant at the 1-percent level.
** Statistically significant at the 5-percent level.
* Statistically significant at the 10-percent level.

Table 6
The Effects of IT on Process Innovation[a]
First Difference Regressions

	Change in Setuptime 97-02	Change in Setuptime 97-02	Change in Runtime 97-02	Change in Insptime 97-02
Percentage Change in Machines 97-02	0.668 (0.207)***	0.465 (0.226)**	0.309 (0.180)*	0.205 (0.228)
Introduced Flexible Manufacturing 97-02	-0.049 (0.242)	0.265 (0.244)	-0.457 (0.215)**	0.215 (0.268)
Introduced Automatic Sensors 97-02	-0.057 (0.281)	0.319 (0.314)	0.279 (0.240)	-0.712 (0.315)**
Introduced Computer Aided Design 97-02	-0.008 (0.187)	-0.047 (0.203)	-0.266 (0.160)*	-0.150 (0.209)
Inverse of Batch size 1997		0.867 (1.648)		
Interact. Chg. Machines – Inv. Batch size		3.592 (1.457)**		
Observations	165	113	159	168
R-squared	0.10	0.28	0.20	0.06

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
a All regressions include controls for age of plants, number of shopfloor workers and dummy for unionization

Table 7
The Effects of HRM on Process and Product Innovation [a]
First Difference Regressions

Dependent Variable	Change in Setuptime 97-02	Change in Runtime 97-02	Change in Insptime 97-02	Change in Batch Size 97-02
Percentage Change in Machines 97-02	**0.711 (0.229)*** **	0.305 (0.200)	0.157 (0.238)	**0.794 (0.264)*** **
Introduced Flexible Manufacturing 97-02	0.148 (0.277)	**-0.424 (0.246)* **	0.285 (0.291)	0.031 (0.313)
Introduced Automatic Sensors 97-02	0.002 (0.322)	0.343 (0.279)	**-0.822 (0.334)** **	0.175 (0.407)
Introduced Computer Aided Design 97-02	-0.003 (0.210)	-0.186 (0.180)	-0.101 (0.220)	0.186 (0.260)
Technical Training Introduced 97-02	**-0.409 (0.296)* **	**-0.452 (0.250)* **	-0.150 (0.308)	0.005 (0.365)
Introduced Teams 97-02	0.343 (0.245)	0.192 (0.203)	-0.355 (0.256)	0.015 (0.305)
Introduced Basic Training 97-02	-0.539 (0.338)	0.073 (0.286)	-0.469 (0.355)	-0.260 (0.402)
Observations	145	140	150	107
R-squared	0.15	0.21	0.08	0.11

Standard errors in parentheses
*Significant at 10%; ** Significant at 5%; *** Significant at 1%
[a] These regressions include controls for age of plants, number of shopfloor workers, and dummy for unionization

Table 8

The Effects of IT on Importance of Different Types of Skills [a]

Dependent Variable: Equals One if Skill's Importance Increased Between 1997 & 2002

	(1) Math	(2) Computer	(3) Programming	(4) Problem-Solving	(5) Cutting Tools	(6) Multiple Machines
IT Measure for:						
1. Specification 1: Number of New Technologies Introduced 1997-2002[b]	0.079	**0.604**	0.032	-0.101	0.018	-0.03
	[0.101]	**[0.178]***	[0.127]	[0.104]	[0.104]	[0.115]
2. Specification 2: Dummy Variable for Introducing New Technologies 1997-2002[c]	-0.002	**0.779**	0.105	-0.076	-0.061	-0.023
	[0.194]	**[0.275]***	[0.234]	[0.199]	[0.203]	[0.230]

Robust standard errors in brackets

* significant at 10%; ** significant at 5%; *** significant at 1%

[a] Each entry in this table reports the coefficients on the IT measure from 12 different regressions. All regressions include controls for age of plant, number of shopfloor workers, and dummy for unionization.

[b] This is the sum of four dummies which each equal one if plant added any of the pieces of IT equipment (Fms, Autosens, Cadcam) or if number of machines went down

[c] Dummy that equals one if plant added any of the pieces of IT equipment (Fms, Autosens, Cadcam), or if number of machines went down.

Table 9
Determinants of Adoption of New IT Between 1997 and 2002
(Probit Estimates) [a]

A. Adoption of New CNC

	(1)	(2)	(3)	(4)
Hi Comp Lo Conc	0.257*** (0.074)	0.246*** (0.074)	0.234*** (0.076)	0.235*** (0.067)
Hi Comp Hi Conc	0.214** (0.076)	0.233** (0.070)	0.222** (0.072)	0.168* (0.070)
Lo Comp Hi Conc	0.072 (0.095)	0.078 (0.090)	0.055 (0.096)	0.068 (0.090)
Big		0.247*** (0.011)		
Big Specialized			0.354*** (0.099)	0.267*** (0.103)
Big Commodity			0.158 (0.091)	0.064 (0.095)
Small Commodity			0.180 (0.076)	0.109 (0.089)
Adoption of New HR				0.184** (0.078)
N	118	118	116	105
Pseudo R^2	0.076	0.119	0.172	0.241

B. Adoption of New CNC or FMS or Autosens

	(1)	(2)	(3)	(4)
Hi Comp Lo Conc	0.210** (0.07)	0.201** (0.070)	0.202** (0.070)	0.187*** (0.059)
Hi Comp Hi Conc	0.172** (0.072)	0.186** (0.067)	0.187** (0.067)	0.127** (0.060)
Lo Comp Hi Conc	0.109 (0.084)	0.111 (0.083)	0.109 (0.084)	0.122 (0.072)
Big		0.195** (0.105)		
Big Specialized			0.281*** (0.095)	0..169* (0.092)
Big Commodity			0.166* (0.091)	0.076 (0.770)
Small Commodity			0.188* (0.052)	0.126 (0.053)
Adoption of New HR				0.193*** (0.071)
N	118	118	116	105
Pseudo R^2	0.055	0.088	0.135	0.218

[a] Probit coefficients (evaluated at the mean) and standard errors are shown in the table. The specification in column (3) was also estimated with OLS. The OLS coefficients for Panel A are .325 + .28 Hi Comp Lo Conc + .27 Hi Comp Hi Conc + .08 Lo Comp Hi Conc + .38 Big Custom + .20 Big Commodity + .29 Small Commodity. For Panel B, the OLS coefficients are .364 + .26 Hi Comp LoConc + .25 Hi Comp HiConc + .15 Lo Comp Hi Conc + .33 Big Custom + .24 Big Commodity + .36 Small Commodity.
HiCompLoConc = high number of competitors and not highly customer-concentrated; HiCompHiConc = high number of competitors and highly concentrated; LoCompHiConc=low number of competitors and highly concentrated.

* - Significant at 10% Level ** - Significant at 5% Level ***- Significant at 1% Level