How Does Information Technology Affect Productivity?
Plant-Level Comparisons of Product Innovation, Process Improvement and Worker Skills

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ABSTRACT

To study the effects of new information technologies (IT) on productivity, we have assembled a unique data set on plants in one narrowly defined industry – valve manufacturing – and analyze several plant-level mechanisms through which IT could promote productivity growth. The empirical analysis reveals three main results. First, plants that adopt new IT-enhanced equipment also shift their business strategies by producing more customized valve products. Second, new IT investments improve the efficiency of all stages of the production process by reducing setup times, runtimes and inspection times. The reductions in setup times are theoretically important because they make it less costly to switch production from one product to another, and support the change in business strategy to more customized production. Third, adoption of new IT-enhanced capital equipment coincides with increases in the skill requirements of machine operators, notably technical and problem-solving skills, and with the adoption of new human resource practices to support these skills.

I. Introduction

This study presents new empirical evidence on the relationship between investments in new computer-based information technologies (IT) and productivity growth. While rapid advances in computing equipment have spawned hosts of new information technologies that have undoubtedly reshaped the economy in many ways, evidence from industry-level and economy-wide studies on the timing and industry location of IT investments suggests that new IT may be responsible for the accelerated productivity growth of the 1990's (Jorgenson, Ho and Stiroh, 2003; Oliner and Sichel, 2000). To better understand the relationship between investments in IT and productivity growth, we have assembled a unique plant-level data set in one narrowly defined industry, valve manufacturing, and analyze several plant-level mechanisms through which IT could promote productivity growth including the effects of IT investments on production process efficiency, product customization, worker skills and work organization.[1]

These unique data permit particularly convincing empirical tests of the effects of IT. The homogeneity of the plants' production processes within this narrowly defined industry together with the estimation of longitudinal models eliminate many sources of unmeasured heterogeneity that confound productivity comparisons in more aggregated data and in broader samples. Also, industry-specific measures of IT are more detailed than expenditures on computing equipment or employees' use of computers, and instead identify specific types of IT-enhanced capital equipment used in valve manufacturing. The IT measures vary across stages of production within a plant and permit the estimation of within-plant stage-specific models of the effects of IT.

The empirical analysis reveals three main results that highlight how the adoption of new IT-enhanced machinery involves much more than just the installation of new equipment on the factory floor. First, valve manufacturers that adopt new IT-enhanced equipment also shift their business strategies and begin producing more customized valve products. Second, new IT investments improve efficiency of all stages of the production process by reducing setup times, run times and inspection times. The reductions in setup times are theoretically important because they make it less costly to switch production from one product to another, and support the

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[1] Examples from the extensive literature on the effects of computer technologies on worker skills are Autor, Katz and Kearny (2005), Autor, Katz and Krueger (1998), Autor, Levy and Murnane (2003), Caroli and van Reenen (2001), Dunne and Schmitz (1995), Dunne, Haltiwanger and Foster (2000) and Doms, Dunne and Troske (1997). Bresnahan, Brynjolfsson, and Hitt, (2002), Black and Lynch (2001), Bresnahan and Greenstein (1996), and Mendelson (2000) present evidence on the link between computer-based IT and new work practices.

change in business strategy to more customized production. Third, adoption of new computer-based IT coincides with increases in the skill requirements of machine operators, notably technical and problem-solving skills, and with the adoption of new human resource practices.

While an obvious limitation of such a plant-level study from a single industry is its generalizability, the increases in process efficiency and product customization that we document for valve manufacturing characterize many industries during the 1990's. Research on service sector industries including call centers, hospital emergency rooms, and concert entertainment offer examples in which increases in process efficiency and customization of services are often accompanied by the adoption of new computer-aided IT (Gabor, 2004). Just as new IT promotes more customized production by reducing setup times for valve makers, faster information processing technologies foster customization in these industries by reducing the time it takes to prepare a customized telephone script for the next customer, a customized evaluation and treatment of a new patient, or a customized ticket package for the next concert fan with prices tailored to that day's demand.[2] While new IT appears to promote customization of products and services in many industries, documenting these productivity-enhancing effects of new computer-based technologies requires the kind of detailed data we have collected on product varieties, operating efficiencies, worker skills, and work practices from plants in a single industry.

Sections II and III describe the valve-making production process, present case study regression results from one plant, and develop a theoretical model of the decision to invest in new IT and its effects on productivity. Sections IV through VIII describe our survey data and present econometric evidence on the relationship of new IT investments to process efficiency, product innovation, worker skills and work practices. Section IX concludes.

II. The Valve-Making Production Process

A detailed investigation of how IT investments affect productivity, skill demand and work organization requires rich establishment-level data. We ground this study in the context of a single narrowly defined industry, valve manufacturing, to make the measures and models of IT investment and productivity growth more convincing. This section reports on observations from visits to five plants that we use to inform the study's data collection efforts, theoretical model,

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[2] Michael Rapino, CEO of Clear Channel reported that his concert production business "used to be fairly generic: three ticket prices and maybe a T-shirt and a hat. [Now it] has become a lot more about customization. There's an incredible amount of pressure to innovate." USA Today, September 27, 2005, p. 2B. For evidence on how the Internet has increased product variety, see Brynjolfsson, Smith and Yu (2003). For an intra-industry study documenting productivity increases due to computerization, see Hubbard's study of trucking (2003).

and empirical tests. We first describe the industry's production process and how innovations in IT have changed the process. The section concludes with an analysis of detailed performance and technology data from one plant.

IT and the Production Process for Valve Manufacturing

A valve is a metal device attached to pipes to regulate the flow of liquids or gases. Valves can be a commodity product, such as valves that control the flow of air in standard air conditioners, or a highly customized product, such as valves built to order for a new chemical plant or a submarine. The production process in valve making is a machining operation.[3] A valve is made by taking a section of raw material and completing several processes on one or more machines, such as machining threads at each end for screwing the valve to pipes, boring holes at different locations to attach control devices, and manufacturing and assembling various devices that control the flow.

Forty years ago, skilled machinists used machine tools to manufacture valves manually Today, valve manufacturing is highly automated with new computer-based IT features embedded directly in valve manufacturing machines. The central piece of equipment is a *computer numerically controlled (CNC) machine* that fixes the raw material on the pallet of the machine and automatically machines the valve component using commands entered as code into the machine's operating software.[4] The *CNC controller* box, the main IT element of these machines, tells the CNC machine exactly what to do – where to cut, how deep, the angle of the cut, the diameter, how many times to cut, how to move the steel to re-cut, and so on. CNC machines are now in widespread use in the industry.

Today, substantial amounts of information processing technology and computing power are embedded directly into new CNC machine controllers. Because the computing power is embedded inside controller boxes, only field research under the guidance of experts in these technologies can identify the IT features of new CNC machines and how these features change and improve valve production. We describe three of the most important IT-based improvements in CNC's in recent years – fusion control, greater axis capabilities, and more efficient software.

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

[4] 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. The earliest CNC machines were introduced in the 1970's and controlled by punched paper tapes that were programmed off line by programmers and then fed to the machines via tape readers. Manual, NC, and CNC machines of different vintages all still exist in the industry, but sophisticated CNC are now dominant as our survey data below will show.

After 1998, CNCs were equipped with "fusion control." This computer control feature contains more flash memory with sophisticated programs that improve CNC productivity in several ways. First, these new controls reduce machine setup time – the time it takes operators to give CNC's the directions on how to turn and cut the steel to make the valve and to change parts in the machine -- since the programs in fusion control are more conversational, and far simpler to complete. Second, a key part of the setup process is that operators must "qualify" a job by making a test run that produces the part and then adjusting the program to correct any errors. During this setup time, the operator must setup a rack of tools or fixtures inside the machine that are used for the cutting process, and the CNC accesses these tools. New fusion controllers decrease the time it takes to qualify the part by making fewer errors in the initial programming and by automating the process of getting the right cutting tools into the CNC's tool rack. In sum, the more sophisticated fusion controller will speed up the process of programming the many tasks of machining and adding fixtures, thus leading directly to reductions in machine *setup times*. Fusion control was standard in new CNC machines by 2003.

New advances in computerization of the CNC have also reduced *run-time* – the time it takes CNC machines to perform the machining processes. New CNC controllers have improved the 'axis capabilities' of these machines. Newer 5-axis CNC millers can machine a valve component on five different angles or axes in one "fixturing" operation. An older 3-axis CNC machine tool would require the valve to be manually repositioned within the machine tool to machine on a fourth or fifth axis. Run times are shorter on CNC machines with greater axis capabilities when they eliminate the need for any such repositioning. IT advances also allow the CNC controller to use its computing resources more efficiently. An example is "curve interpolation," which allows CNC machine tools to create smooth curves on a valve component instead of having to approximate curves using a large number of linear cuts. These software advances permit more sophisticated machining operations with smaller programs that use less memory to perform a given task. Smaller programs are also easier to edit, troubleshoot and optimize thus reducing setup and run-times.

Overall, managers report that efficiency gains of newer CNC machines are not so much a matter of reductions in time it takes to complete a given cutting or drilling task since there are limits on the speed that any equipment can machine a specific type of material. Rather, newer CNC machines are more "flexible" – they can perform a much greater variety of operations on one CNC machine, thereby eliminating the need to switch the block of raw material across multiple machines or to stop the machine to reposition the block for the next machining operation. In plant visits, it was common to hear how the production of a particular valve part today can be machined on just one or two CNC machines, whereas in the past it would require the use of many more CNC machines that could cut at different angles and positions or that could only use smaller sets of machine tools in their racks. For example, at one plant, producing a typical product required seven machines in 1980; by 2002 that same product is made with only two CNC machines that are more sophisticated.

These observations are important for construction of the CNC technology variables used in the empirical work in this study. We measure *improvements in CNC quality* by whether there was *a reduction in the number of CNC machines used to produce a given product*. Because IT is completely embedded in new CNC machines, managers stated that a decrease in the number of machines used to produce a given product reflects an increase in degree of 'computerization' for newer versus older CNC machines, and was also relatively simple for managers to identify.[5]

A second technological advance in valve manufacturing is the use of *flexible manufacturing systems* (*FMS*) which is the use of a main computer that sends instructions to sets of CNC machines simultaneously to coordinate their machining operations when these machines jointly produce a product. FMS helps optimize decisions about which parts of a valve should be produced on which CNC machine, thereby reducing runtime. FMS also automatically monitors which cutting tools the CNCs are using and reduces the number of tool changes that are required as the controller allocates jobs across different CNC machines, which also reduces run times. The computerized instructions that coordinate machining tasks across different CNC machines can also reduce the time it takes to complete setup tasks.[6]

Finally, our interviews identified IT advances that reduce the *inspection time* in the quality control process. Each dimension of a complicated valve often must be produced to an

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[5] Longitudinal data from the single plant case study reported in this section as well as cross-plant data from our own survey reported in the next section strongly support managers' claims that a reduction in the number of CNCs it takes to produce a given product reflects an improvement in CNC technology and quality. We considered asking about alternative measures of CNC quality in the plant-level survey we describe below, such as the current depreciated monetary value of a CNC, auction prices of CNC machines, or extensive listings of CNC capabilities. However, given the large number of machines that most plants have and their different vintages, survey questions on these features were too difficult and time consuming to answer in pilot surveys. Data on these kinds of measures from other sources were either unavailable or could not be linked back to plants in the survey we developed.

[6] Some plants that implement FMS also put higher-quality controllers on their CNC machines, which reduces setup time and runtime. In the setup and run time regressions below, this would show up as a return to FMS.

accuracy of 1/1000 of an inch, so inspection is a critical part of the production process. For many years, employees did time-consuming inspections with manual measuring devices. Over the last several years, *automated inspection sensor* machines have been introduced which use a touch-probe technology. Operators touch each feature of the valve with sensor probes and the automated inspection equipment then uses data from the probes to compare dimensions of the actual valve to the three-dimensional picture of the valve that was created from the original machine instructions. The newest inspection technology allows inspection to be done without any human contact. Inspection equipment surrounds the valve, operates the probe to measure its features, and checks measurements against specifications.

Another technology that is becoming more common in valve plants is *three-dimensional computer-aided-design* (*3D-CAD*). This is a constantly advancing IT for turning customers' valve specifications into a specific design. This product design software should have its most direct impact on the plant's capabilities of designing more complex products and reducing the time that elapses between the customer placing an order and plant management presenting its design back to the customer.

Managers we interviewed consistently underscored two operational imperatives for remaining competitive in this industry. First, filling customer orders quickly is important since many plants can produce a given customer's order. The reductions in setup, run, and inspection times made possible by new IT are therefore also critical. But managers also emphasized the importance of a second area of competition in the industry – product innovation and customization. Production of more standardized commercial valves is moving abroad to low wage countries, so U.S. valve-makers are relying on a strategy of increasing their capabilities of customizing valves to meet specific customers' needs. According to these interviews, many U.S. valve makers have been increasing the number of customized products they make while reducing sales of standardized catalog products.

The IT advances described in this section also play a critical role in a move toward product customization. As more sophisticated controllers make changeovers between product runs faster and therefore less costly, plants will be able to start producing a greater number of different products in smaller manufacturing lots. New controllers in CNC machines that produce a valve component more accurately and with a greater number of features also allow plants to produce more product varieties at a reduced cost.

Econometric Case Study Evidence: the Effects of IT on Process Efficiency

Managers at one of the five plants we visited provided us with their own proprietary data. These data illustrate several important points about how to measure operating efficiency in this industry. First, product heterogeneity is important. The data describe the production of 331 distinct valve products that the plant made during 1999-2003. Second, plants track operations in distinct stages of valve production. Data for this plant are available on setup-time and run-time but not inspection time. For this plant, the largest component of production times was in setup. Managers indicated their plant was not unusual in this respect.

These longitudinal, product-specific data provide the opportunity to examine productivity gains over time as the plant introduced new valve-making technology. We estimate models that control for product-specific fixed effects that express setup time and run time as a function of changes in production technology. The plant did not introduce FMS technology during the period but has continually purchased new CNC machines to raise the quality of the machines in use. As described in other plant visits, machine operators here concurred that the best measure of CNC quality that we could use from the available data was the number of machines used to produce a given product – the introduction of a new higher quality CNC machine into the production process for a given valve routinely means that more than one CNC machine of an older vintage is replaced.[7] Based on these arguments from operators and managers at the plant, we define the technology variable, *"CNC Quality,"* as the negative of the number of CNC machines used to produce the product and enter it as a determinant of production times. Because these models control for product-specific fixed effects, the coefficient on the CNC Quality variable in these models estimate the changes in setup and run times required to make a given valve after the plant begins making that specific product with a smaller number of more sophisticated machines.

A reduction in the number of machines used to make a given valve product undoubtedly reflects the use of new machines with greater capabilities since the smaller number of machines executes all of the tasks that a larger number of machines had to execute to make the valve. What is not clear is whether the smaller number of newer, more flexible CNC machines can be set up and then complete the run time tasks faster than before when a larger number of machines were used. If the smaller number of newer, more advanced CNC machines is also easier to set

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[7] In our larger survey dataset that is described below we find that plants that reduce their number of machines to produce a given product between 1997 and 2002 are plants that also report purchasing new CNC machines during the same period. Purchasing new machines allows plants to use fewer new machines to make a given product.

up and can also accomplish the run time tasks faster, then the coefficient on this CNC quality variable in these product-specific change-in-production-time equations will be negative.

The sample for these product-specific setup time and run time models includes observations for valves that were in production at some point during the 1999-2003 time period and that had been produced at least two different times. Some data on these valves extend back prior to 1999, but 75% of the observations are for 1999-2003. This data set contains 790 observations for 331 distinct valve products. The product-specific observations include data on the total number of CNC machines used to make each product and the scheduled setup-time and runtime for each machine used.

When these production time models with controls for product-specific fixed effects are estimated, the results in Table 1 are obtained. An increase in CNC quality (a reduction in the number of CNC machines used to make a product) significantly decreases both setup and run times. Not only can a smaller number of newer, more flexible machines make the same valve that was previously made by more machines, they can make the valve faster. The log(setup-time) regression shows that a 10 percent reduction in the number of machines used to make a given product (i.e. an increase in the quality of the CNC machines used) reduces setup-time by 9 percent (Table 1, column 1). Equivalently, when we estimate these equations without taking logs, the coefficient on the "number of machines" variable is -55.7 minutes. A decrease of 55.7 minutes due to a one machine decrease in the number of CNC machines used to produce a valve product is 11% of the median setup-time of 495 minutes for this sample. Moreover, the R-squared is large -- for the overall regression it is .60; for the within effects (i.e., by product) it is .42; and for the between effects it is .68.

The effects of an increase in the CNC quality variable are also sizable in the run-time equation. A 10 percent decrease in machines (increase in CNC quality) reduces run-time by 6 percent. However, because typical run-times (at 46 minutes for an average run) are much shorter than setup-times, the most important quantitative gains are in setup-time reduction. Note that the inclusion of a year time trend variable in the column 2 and 4 models has little effect on the estimated effects of the variable measuring the number of machines used to produce the valve. The time series that we have for most valve products is very short, and perhaps as a result, we find no strong time trend reduction in either the setup-time or run-time models.

While the estimates from the product-specific regressions in Table 1 imply large reductions in production times, especially setup times, when the plant introduces a smaller number of more advanced CNC machines to produce a given valve product, two factors determine the exact size of the *CNC quality* coefficients in these regressions. First, the higher the quality of the new CNC machine introduced into the production process, the greater is the reduction in setup-time. Not all products use exactly the same CNC machines. The point estimates on the coefficient on the CNC quality variable in the Table 1 regressions reflect the average increase in quality of the CNC machines purchased. Second, the most complicated products that require especially long setups may benefit the most from purchasing new CNC machines to produce these products. But according to the calculations above, for a typical product at this plant, a switch from an average set of older CNC machines to an average set of newer CNC machines reduces setup time by 9% or 56 minutes.

The regression results from this case study reinforce the observations that managers made during our plant visits. Improvements in CNC quality, as measured by the reduction in the number of machines used to produce a given product, reduce setup-time significantly. To a lesser extent, improvements in CNC quality reduce run-time. The mechanism underlying the results of these simple regressions is clear: a reduction in the number of machines occurs only because the quality of the CNC technology is better. When a plant produces a given valve product with fewer more advanced machines, setup-times and run times go down.

III. Theoretical Framework of the Impact of IT

Valve manufacturing is a batch process. Products in many other manufacturing industries are also made in batches. Each compound in chemical production, each book in publishing, and each new piece of furniture in high volume furniture production is a new batch. Even in services, each new customer often creates a new ‘batch’ of orders that require separate adjustments. In all of these settings, just as in the econometric case study of the valve manufacturer above, the setup-time when machines are reconfigured from the requirements of one product run to the next is often a large part of overall production time. We posit that an important consequence of the dramatic reductions in the price of information technology is that setup costs are dramatically lower after firms adopt new production machinery that has IT improvements embedded in the machinery. Previously, switchovers between product runs entailed a great deal of hands-on adjustments of machinery by knowledgeable machine operators. With new machinery, a portion of the setup is made as easy as touching a screen on a computer that sends the machine instructions for making the machine part.

To clarify the tradeoffs that firms face with improvements in information technologies, we model the change in profits that would be expected from falling prices of information technology. Assume that there are two product classes – commodity products (co) and customized products (cu). Commodity products are typically listed in a company's catalog and customers must order these products exactly as they are described in the catalog. Customized products may be variants of a commodity product but they are made to the customer's specification. Since customized products are made to fill a customer's specific order, they are made in shorter runs. The batch size for customized products (B_{cu}) is larger than batch size for commodity products (B_{co}), all else constant. Assume for simplicity that these batch sizes are fixed for each product class and thus $B_{cu}<B_{co}$. Given these fixed batch sizes for the two classes of product, the firm maximizes profits, π, by deciding how many production runs of the customized product, N_{cu}, and how many runs of the commodity product, N_{co} , to undertake:

$$(1)\quad p = N_{cu}B_{cu}\,[P_{cu} - (\text{unit cost})_{cu}] + N_{co}B_{co}\,[P_{co} - (\text{unit cost})_{co}] - P_{IT}IT$$

Unit costs in (1) are a function of setup time (S_{co} or S_{cu}), runtime (R_{co} or R_{cu}), inspection time (I_{co} or I_{cu}), materials costs (M_{co} or M_{cu}), design and sales time (D_{cu}):

$$(2a)\quad (\text{unit cost})_{cu} = (w+r)\,(S_{cu}/B_{cu} + R_{cu} + I_{cu}) - M_{cu} - D_{cu}/B_{cu}$$

$$(2b)\quad (\text{unit cost})_{co} = (w+r)\,(S_{co}/B_{co} + R_{co} + I_{co}) - M_{co}$$

where $p \equiv$ profits

$S_j \equiv$ hours to setup machine to run a batch of product; $j = co, cu$
$R_j \equiv$ hours to run each piece of product; $j = co, cu$
$I_j \equiv$ hours to inspect each piece of product; $j = co, cu$
$D_{cu} \equiv$ added cost of design and promotion for customized products only
$B_j \equiv$ average batch size (number produced per scheduled batch) $j = co, cu$
$N_j \equiv$ number of batches of product j; $j = co, cu$
$M_j \equiv$ materials costs per unit; $j = co, cu$
$P_j \equiv$ average price of product j, $j = co, cu$
$w \equiv$ wage rate
$r \equiv$ maintenance cost of capital
$P_{IT}IT \equiv$ price of new IT-imbedded machines times the quantity of IT-embedded machines

In equation (1), profits in the short run are a function of the difference between the revenues and the time costs of production, minus the materials costs and the cost of the CNC machines. The time costs of production are the wage and the rental cost of capital for the time that it takes to produce the product. Thus, productivity increases if production time falls. Finally, for customized products, we assume that there is a design and marketing cost, D_{cu}, reflecting the cost of the specialized design of the product and the cost of finding customers for these products.

Underlying the model is the assumption that each hour of machine time requires an hour of operator time, or that $L_j = (l_1 S_j + l_2 R_j B_j + l_3 I_j B_j)$; for $j = co, cu$, where $l_1 = l_2 = l_3 = 1$ if one person runs each machine, which is a reasonable approximation for valve manufacturing. Next, assume that all three components of production time, setup, run and inspection times, are a function of IT-imbedded capital and other variables:

(3) $S_j = f^{Set}(IT_j^{Set}, \text{Skill}, X)$, for $j = co, cu$

(4) $R_j = f^{R}(IT_j^{R}, X)$, for $j = co, cu$

(5) $I_j = f^{I}(IT_j^{I}, X)$, for $j = co, cu$

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 is a vector of control variables. In (3), we also assume that a more skilled or highly trained operator can do a setup in less time, an assumption described in more detail below.

With this model of the manufacturing process, how do falling prices of IT and the availability of more technologically sophisticated CNC machines affect the firm? We focus on five changes. First, firms purchase more IT; a decrease in P_{IT} raises IT all else constant. Second, production process efficiency should rise; setup time, runtime and inspection time should fall when plants adopt IT machinery relevant to these processes. Thus, in equations (3)-(5), we assume that $?S_j/?(IT) < 0$, $?R_j/?(IT) < 0$, and $?I_j/?(IT) < 0$. This is an assumption rather than a prediction of the model, but one that is consistent with evidence from our plant visits and the econometric results from the case study in section II.

Third, the firm makes a strategic move towards producing more customized products. This change occurs because IT reduces setup costs. As setup time falls, the unit cost of production falls, and as equation (2) shows, the reduction in unit costs due to a reduction in setup time is greater for customized products than for commodity products. Setup costs are a bigger fraction of unit costs for customized products, because $(?(\text{unit costs})/ ?S_j = 1/B_j)$ and $B_{cu} < B_{co}$. Given this falling cost of customized products relative to commodity products, plants increase their production of customized products, all else constant.[8] Even if customized products and commodity products are produced in the same batch sizes so that the impact of IT on unit costs (net of design costs) is the same for both classes of products, plants would increase their customized production if customized products sell at higher prices.[9] Finally, another reason that IT will induce a move towards greater production of customized products is that some advances in IT, such as computer-aided design, lower design costs which, according to our model, are only relevant for customized products.

Fourth, increased investments in IT-enhanced machinery affect optimal skill demand but the direction of this effect is ambiguous. In equation (3), we assume that skilled workers are used primarily for machine setups.[10] Given this assumption, there are three effects associated with the optimal change in setup-time after new IT machinery is purchased that make the overall impact of IT on skill demand unpredictable. First, if setup time is reduced as a fraction of total production time (i.e., relative to runtime), then skill demand will fall since setup requires the most skilled workers. This would be true if plants did not change their product mix. However, plants should also shift to more setup-intensive products – i.e. customized products that have higher setup time relative to total runtime – which would increase skill demand, thereby offsetting the first influence of IT. The net effect of these two factors can not be predicted. A third factor not explicitly incorporated in the model above, however, could also affect the specific types of skills in demand. In the past, operators would have utilized routine machining skills to produce a valve (i.e. positioning the valve correctly on the machine and then choosing

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[8] Thus, firms move towards customized production if they are price takers and product prices are unchanged. Also domestic firms are even more likely to be moving towards customized products because the price of commodities is falling due to lower labor costs for unskilled labor abroad. In their model, Milgrom and Roberts (1990) make the assumption that their multi-product firm faces a downward sloping demand curve and then solve for the optimal amounts of output and other control variables. Likewise, to solve for the optimal amounts in our model, we would need to place constraints on the model that would limit the optimal output, such as downward sloping product demand and/or non-linear adjustment costs for changing the plant size or for finding new customers. For the valve industry, we envision both of these constraints. That is, firms are price takers for small increases in their output, but as output rises too much, the market is saturated and prices fall. Similarly, we are modeling the short run decision to become more customized, and in the short run, the costs of significantly increasing the size of the plant or seeking large numbers of new customers are accelerating, and therefore limit the increase in the optimal amount of customized product that is produced. Thus, our model of changes in product mix and IT purchase should be considered a model of short-run marginal changes.

[9] Customized products are likely to sell at higher prices than commodity products because of greater competition in the commodity market, especially from foreign producers who have lower labor costs.

[10] A skilled worker could also reduce runtime, by, for example, solving problems as they arise during the running of the job. For simplicity, we assume that skills affect only setuptime, because skills are likely to have a greater impact on setuptime. In the empirical section below we provide a richer description of skill demand for all jobs.

the cutting tools from the tool fixture and moving the tools into place). Interviews during our plant visits offered examples of how new computer technologies have changed the nature of skills demanded as the routine machining skills are increasingly done automatically by the newer CNC machines, while the demand for non-routine problem solving skills that are required to set up, monitor and correct the new sophisticated CNC machines appear to increase.

Finally, while the role of innovative human resource management (HRM) practices is not considered in the model above, a number of models (Milgrom and Roberts, 1990; Bresnahan, Brynolfsson and Hitt, 2002) conclude that the adoption of technically complex manufacturing equipment may require the adoption of new types of work practices, such as enhanced training in the new technologies and teamwork to solve technical problems. The data for this study permit us to examine whether the adoption of new technologies coincides with changes in HRM practices. In summary, we will test the following five hypotheses in the empirical work:

> H1: Given falling costs of IT, there will be an increase in the adoption of IT-enhanced machinery. In the valve making industry, the IT-embedded machines include new CNC machines, FMS, computerized inspection equipment, and new 3D-CAD software.
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> H2: New IT-enhanced machines improve production process efficiency. Setup time, run time and inspection time fall after new IT-enhanced equipment in these stages is adopted.
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> H3: New IT promotes product customization and innovation.[11] New 3D-CAD technologies should directly affect the plant's capabilities of designing more customized valves, while other technologies that reduce setup time would also promote customization.
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> H4: IT adoption may increase (or decrease) skill demand.
>
> H5: IT adoption may require new HRM practices.

An overarching point of these hypotheses is that investments in new IT-enhanced production equipment trigger an extensive set of changes for the business, including a change in the overall business strategy with the firm competing less in terms of lowering the production costs of commodity products and more in terms of customizing products to the needs of specific

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[11] Note that we are modeling the form of customization that requires product redesign and labor-intensive reconfiguring of machines in the setup process to produce a product that has never been produced before. Others have modeled 'mass customization,' as when customers can 'customize' their computer from a pre-set menu of options from the pc manufacturer. Mass-customization would have very different implications for skill demand. See, for example, the model of "competitive customization" by Pardaktark and Mendelson (2004) and the work cited therein.

customers.[12] In this way, our model complements other recent studies that model the effects of technological shocks on business strategy and skill demand. Goldin and Katz (1998) study the emergence of new technologies during the early part of the 20th century and the ensuing evolution of production methods from manual production to factory assembly to continuous-process batch methods, and emphasize the increase in skill demand and the proliferation of new products that accompanied these changes. Similarly, Mobius and Schoenle (2006) show how the greater product variety permitted by new information technology results in less predictable product demand which in turn increases the demand for more flexible or skilled workers. As in these prior studies, our model also posits that investments in new technology leads to greater product customization and variety, and may also lead an increase in demand for skills among shopfloor operators in this manufacturing industry.[13]

IV. The Valve Industry Survey

The plant visits and interviews with industry experts identify concrete examples of new IT-enhanced equipment and how these IT advances impact various stages of the production process. Several observations from this field research about the effects of new CNC technologies on setup and run times are supported by the econometric case study results shown in Table 1. To examine the impacts of IT investments on a broader set of outcomes beyond setup time and run time across a broad sample of plants in this industry, we developed a customized survey for valve plants. The field research informs how we designed survey questions that would yield reliable measures of investments in new IT-enhanced production machinery, changes in the setup, run, and inspection stages of valve-making, and the extent of customization of a plant's valve products. The survey also collects information on worker skills and HRM practices.

The Sample of Valve Industry Plants

After conducting the field research, we designed, pre-tested, and conducted a customized industry survey in 2002.[14] To identify the population of U.S. valve-making plants for this survey,

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[12] The idea that the firm's strategy should change in response to an input price change was emphasized in exactly our context by Milgrom and Roberts (1990) in their description of the shift to "modern manufacturing" resulting from falling prices of IT. In their model, the entire "system" of production changes, resulting in more frequent product redesign, higher product quality, more frequent setups of smaller batches, lower inventories and faster shipment times.

[13] See Chandler (1977) and Goldin and Katz (1998) for further evidence on the technological changes in the last century that increased the demand for skills and education on the shop-floor or within agriculture.

[14] 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 needed to complete the survey.

we collected contact information from Survey Sampling, Inc. for any plant in a valve-making industry class (SICs 3491, 3492, 3494, and 3593) with more than 20 employees. Of a potential universe of 416 valve making plants of this size, 212 plants, or 51%, provided responses to the survey questions described in this section via telephone interviews.[15] Empirical results in the study are based on the responses from these 212 valve-making plants.[16]

Production Process Efficiency Measures

As the field research reveals, plants produce a range of valve products. This product heterogeneity is an important consideration in developing measures of process efficiency. We therefore use a *product-specific* measure of efficiency gains in the plants' machining processes. We asked each respondent to look up data for "*the product you have produced the most over the last five years*" for the following key indicators of production efficiency:

Setup-Time: *About how much setup-time does (did) it take to produce one unit of this product today (and in 1997)?*

Run Time: *About how much run time does (did) it take to produce one unit of this product today (and in 1997)?*

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

Product Customization Measure

Increases in customization imply changes in the number of products a plant makes. Unlike the process efficiency measures that pertain to one product, this is a *plant-wide* measure about the range of products a plant makes. Based on discussions with managers, we measure the extent to which plants customize products for specific needs of customers with the questions:

Percent Catalog: *In 2002 (1997), what percentage of your customer orders are directly from your catalog with no design change?*

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[15] Of 762 plants that Survey Sampling Inc. lists in the four valve-making SIC classifications, 200 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 the number of 416 valve-making plants.

[16] Non-respondents do not differ significantly from the survey respondents in terms of sales and number of employees (the only two variables available for the non-respondents), according to values of a chi-square test. We were able to match 179 of our 212 plants to the plants in the 1997 Longitudinal Research Database. Comparing our survey plants to the other valve-makers that were in existence in 1997, we found that our survey plants had higher values of shipments, assets, production worker hours and materials costs, perhaps due to the fact that our survey was administered to plants with at least 20 employees according to the employment data reported in SSI.

There were 197 responses for the 2002 question, but only 70 for 1997 data. However, virtually all respondents answered a separate survey question that asked if the percent of orders from the catalog increased, decreased or stayed the same between 1997 and 2002 and we use this question to create categorical variables – percent catalog up, percent catalog down, and percent catalog unchanged – for longitudinal analyses of changes in customization between 1997 and 2002. *Decreases in the percent catalog measure* indicate a decline in the production of standardized products and thus *reflect an increase in the production of made-to-order customized products.*

Information Technology Measures

The survey asks several questions to measure investments in the specific IT-enhanced equipment identified during our plant visits:

Number of CNC Machines Used to Make the Plant's Main Product (CNC Quality Measure): Consider the product you have produced the most over the last five years. In order to produce one unit of this product today (and in 1997) how many CNC machines do (did) you employ?

This is the measure of the technological sophistication of CNC machines that we use in models of product-specific improvements in production times. When a plant decreases the number of CNC machines it uses to produce a given product, then the machines being used have become more technologically advanced.[17] The remaining IT variables are plant-wide variables.

Total Number of CNC Machines in the Plant: How many CNC machines does the plant have?

Additional survey questions ask for the year the plant purchased its first CNC machine and the year the plant purchased its most recent CNC machine.

Flexible Manufacturing Systems (FMS): Does the plant have FMS technology (where two or more CNC machines are controlled by computers) and what was the year of adoption?

Automatic Inspection Sensors (Auto Sensors): Does the plant have automated inspection sensor equipment and what was the year of adoption?

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[17] As discussed above in the descriptions of technologies observed in the plant visits, we might prefer to measure whether CNC machines have specific IT capabilities (e.g. does the IT on this machine allow the machine to bore holes on multiple axes at the same time), but the number and detail of these questions made them infeasible for a broad-based survey of the industry. The data on other IT variables from this survey support the idea that plants that reduced the number of machines used to produce its main product have also purchased new machines. The correlation between a dummy variable that equals one if the number of machines used on the main product went down after 1997 and a dummy variable that equals one if the plant bought a new CNC machine since 1997 is positive and significant at the 5% level.

Three Dimensional CAD software: Does the plant use three-dimensional CAD software for designing new products and in what year was this software first used?

Other plant-level survey questions concerning the importance of different types of worker skills and human resource management practices are described below with the empirical results.

VI. Information Technology and Production Times

This section reports estimates of the effects of the adoption of new IT-enhanced production equipment on measures of production process efficiency in three separate stages of the valve making process. Because of the considerable heterogeneity of the many valve products made in different plants, these models estimate the effects of changes in IT on changes in production times for the plant's main product. Before reporting results of these models, we present trends in adoption of IT equipment and in the efficiency measures.

Trends in the Adoption of IT

Figure 1 displays results from the survey on the plants' initial adoption of CNC machines, FMS technology, automated inspection sensors, and the three-dimensional CAD valve design technology. From 1980 through 2002, these technologies spread dramatically through the industry. In 1980, roughly one-quarter of all plants had already adopted their first CNC machines, and by 2002, nearly 90% of the sample's plants had at least one CNC machine. FMS and automated inspection equipment were both non-existent in the industry in 1980 and can now be found in approximately one-third of all plants. 3D-CAD technology was first adopted after 1980 in this industry and is now found in nearly three-fourths of all plants with particularly rapid increases in adoption since 1997. Our survey results confirm the most basic hypothesis of this study (H1) – the valve industry has witnessed a dramatic increase in the adoption of four types of IT equipment over time as a result of falling prices of computerization.[18]

The empirical analysis of the effects of these new technologies on production times and other outcomes focuses on the period from 1997 to 2002, and this five-year period also witnessed significant new investments in these technologies. While a vast majority of plants had already purchased their first CNC machine prior to 1997, 74 percent of the plants purchased at least one additional CNC machine between 1997 and 2002. Moreover, our study's measure of CNC

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[18] We do not have hedonic price indices for these machines that document falling prices for each 'unit' of machine quality, but are assured by industry experts that the falling cost of IT (of chips, storage, speed) has reduced prices relative to benefits in these machines. Note also that the survey includes plants that were in existence as of 2002, and so percentages reported in Figure 1 on IT adoption will overestimate the diffusion of these technologies if plants that exited the industry are less likely to have introduced them.

quality – the number of CNC machines used to produce the plant's main product – also changes in this period. The median (and mean) number of machines used to produce a plant's main product was 6 (5.63) in 1997, and declined to 5 (4.97) in 2002. Among the subsample of plants that did reduce the number of machines used to make the main product, the average decline was 1.7 machines. FMS technology, automated inspection sensors, and 3D-CAD technology were also adopted by an additional 15%, 14%, and 39% of our sample of valve making establishments in this five year period. During the 1990s, plants in the valve-making industry invested heavily in new computer-based production technologies.

Trends in Production Times

Table 2 reports summary statistics for production times in 1997 and 2002 for the plant's main product. Setup time statistics refer to the time it takes to set up one run of the product, while run time and inspection times are standardized to the time required for one unit of the product. On average, the time it takes a plant to produce its main valve product declines during the 1997-2002 period, and these reductions in production times occurred in all stages of the production process. The largest reduction was in the setup stage with an average reduction of 68%. The average reductions for the run time and inspection time statistics are 37% and 33% respectively. In all of these cross-plant production time distributions, median production times are always considerably less than mean production times, indicating that setup, run, and inspection times in some plants are relatively high. Comparing median production times in 1997 and 2002, one still finds clear evidence of very large declines in setup times, with smaller reductions in run times and inspection times.

The trends in IT investments and production process efficiency in Figure 1 and Table 2 show that this industry, like the larger U.S. economy, is characterized by increasing investments in new computer aided technologies and improved productivity. To examine whether plants that invest in new IT are the same ones that realize improvements in productivity, we estimate the following first difference productivity models in which time-based efficiency measures are expressed as a function of the adoption of new machining technologies and new HRM practices:

$$(6)\ ?\ \ln(\text{ProductionTime}) = a + \mathbf{b_1 ?\ (NewTechnology)} + \mathbf{b_2 X} + e_1$$

The dependent variable in (6) is the log change in Production Time between 1997 and 2002 – where Production Time refers to setup-time, run time and inspection time. Again, these measures refer to production times *for one product* – the product that the plant produced the most in the 1997-2002 period. The vector **?(NewTechnology)** measures the 1997-2002 adoption of new technologies expected to reduce these machining times – the adoption of higher-quality CNC machines (as measured by the change in the number of CNC machines needed to produce the plant's main product), FMS, or automated inspection sensors. **X** is a vector of controls including the age of the plant, union status, and plant size measured as number of shopfloor workers to test whether the change in production efficiency is affected by these additional factors. The vector of control variables also includes variables that measure the adoption of new HRM practices, such as work teams and technical training programs, during the 1997-2002 period. Because the distributions for each of these production time variables, as well as the change in the production times, has several large outliers,[19] we estimate equation (6) models when possible with both OLS and median regressions.[20]

Estimates of the Effects of Specific Valve-Making Technologies on Machining Times

The regression results reported in Table 3 are consistent with hypothesis H2 that new technologies reduce production times. Plants that invested in new IT-machinery have reduced production times in all stages of production. The results are remarkably straightforward and striking. While the effect of FMS adoption on setup times is sensitive to the choice of estimation method, the results show that the adoption of new technologies into a given stage of the machining process reduces production times in that stage significantly.

As in the econometric case study above, the variable "Increase CNC Quality" is the reduction in the number of CNC machines used to produce the product. The adoption of higher-quality CNC machines reduces setup-time (columns 1 and 2) and runtime (column 3 and 4). Both of these results for this industry-wide sample of valve plants mirror the results from the econometric single-plant case study reported in Section II. Runtime also declines significantly in plants that adopt FMS technology. Results from the median regressions, but not the OLS regressions, show reductions in setup times when FMS technology is adopted. Inspection time declines with the introduction of new automated inspection sensors (column 5). The basic pattern

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[19] In the regression sample, the percentage change in setup time ranges from a minimum of -7.50 to a maximum of 1.10 with a mean of -0.722 and a median of -0.45; 33 percent of the sample has a value of zero and 5 percent has a value less than -2.5. In the case of the percentage change in runtime, the range is from -4.787 to 3.612 with a median of -0.354 and a median of -0.182; 38 percent of the sample has a value of zero and 5 percent of the sample has a value less than -2.08. The percentage change in inspection time ranges from a minimum of -7.09 to a maximum of 4.094 with a mean of -0.382 and a median of zero; 69% of the sample has a value of zero.

[20] Median regressions for the change in inspection time are not estimated as these models do not converge.

of results in Table 3 can be summarized simply. *New IT-based production machinery is associated with an improvement in the efficiency of the stage of production in which it is involved. It does not improve the efficiency of phases of machining in which it is not involved.*

The theoretical discussion of section III draws special attention to reductions in setup times. There we argued that reductions in setup time due to new IT investments make product changeovers faster and cheaper, resulting in a move toward greater customization. These estimated savings in setup times after the adoption of more advanced CNC machines shown in columns 1 and 2 of Table 3 are sizable. According to the means of the production time variables reported in Table 2, setup times in 1997 were the largest component of overall production time, accounting for almost one-half of overall production time. Among plants that experienced an improvement in CNC quality as measured by a decrease in machines after 1997, the median change in ln(machine) is -.54 (or approximately 1.7 machines). A change in the number of machines of this magnitude would reduce setup time by .42 ln-units (using the coefficient on CNC quality in column 2 of Table 3). This is 62 percent of the mean reduction in setup time for the full sample, or 50% of the mean reduction in setup time among those plants that reduced the number of CNC machines used to make their main product. A reduction of 1.7 CNC machines would reduce runtime by .237 ln-units (using the coefficient on CNC quality in column 4 of Table 3). This amounts to 64% of the mean reduction in runtime for the full sample, and 51% of the mean reduction in runtime experienced by plants that did reduce the number of CNC machines used to make their main product.[21]

The efficiency gains resulting from the improvement in CNC quality would increase net revenue for two reasons. First, hourly labor costs per valve fall. Since machine time determines labor time (one person per machine), labor costs fall when machine time falls, and thus net revenue per unit of product rises, all else constant. Since materials costs are unchanged, this should show up entirely as profits (minus the costs of the new IT and assuming no change in competitive conditions). Second, reduced setup time and runtime mean that the plant would be able to run more jobs per year on these new CNC machines, assuming sufficient demand for their valve products.

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[21] The results from the column (2) median regression model indicate that the introduction of flexible manufacturing systems (FMS) reduces setup-time by an additional .184 ln-units, or 1.2 hours; however, the magnitude and significance of the FMS effect on setup times are much less in the column 1 OLS model.

Results in Table 3 also reveal that plants that introduce technical training programs realize an additional reduction in setup times and runtimes. While these efficiency regressions find no effects of teams, it is important to remember that these models pertain only to 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 for a run of a single product than on overall plant efficiency. The results in Table 3 demonstrate that *HRM policies designed to improve the specific skills needed to operate new technologies in the plant are in fact the initiatives that improve the speed of machining operations during a given product run.*[22]

Assessing Potential Biases in Estimated Productivity Effects of IT

The Table 3 results are consistent with a conclusion that new IT equipment improves the efficiency of the production stages in which it operates. However, the IT equipment is not universally adopted, so the question naturally arises whether plants that have yet to adopt the new technologies would actually enjoy the estimated improvements in manufacturing times were they to adopt the new IT equipment or HRM practices. Is the adoption of IT and HRM practices limited because the non-adopters would not experience the kinds of improvements in efficiency suggested by the Table 3 results? Two observations are important when considering the question of whether the coefficients in Table 3 are biased estimates of the effects of new IT investments on production times among current non-adopters.

First, given the nature of the data used and models estimated, we suspect that some potential sources of bias are not important considerations. For example, there is no reason to expect endogeneity in which a decline in setup-time causes a decline in the number of machines in use. Furthermore, results of the stage-specific models reveal that new IT affects specific stages of production in a plant (e.g., automated inspection sensors reduce inspection time but not run time or setup-time, while new CNC's affect setup time and run time but not inspection time). Omitted plant-wide variables that should affect all stages of production, such as the quality of plant management, would not explain this overall pattern of results.[23]

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[22] Unlike others who have found significant interaction terms between IT and HR practices using plant-level productivity measures (e.g.. Bresnahan, Brynjolfsson and Hitt, 2002), we do not find significant coefficients on interaction terms between IT and technical training in the context of product-specific efficiency models that focus on producing one product on a few machines. However, we later show that, at the plant level, the adoption of IT, specifically new CNC machines, and new HRM practices are highly correlated.

[23] The estimated productivity gains from the increased quality of CNC machines could reflect improvements in engineering work on the CNC machines as well as the gains due to computerization of the machines since the use of more advanced CNCs may have to be accompanied by better engineering. Here, however, the interpretation would

Second, despite several useful features of these data, they are still not experimental data with random assignment of IT across plants. Thus, the Table 3 coefficients are still estimates of an average "treatment of the treated" effect – that is, the average expected reductions in production times among IT adopters.[24] Thus, certain sources of selectivity bias can still be important. The treatment of the treated estimates will overstate the effects of IT on production times among the plants that have yet to adopt the IT if IT adopters differ from the non-adopters according to unmeasured characteristics, and these characteristics increase the magnitude of the effects of IT on production times. While the carefully drawn intra-industry sample eliminates many sources of unobserved heterogeneity that could affect the magnitude of the effect of IT investments on production times, one reason why adopters might still experience greater reductions in production times than non-adopters is that the effects of IT may vary with differences in product attributes. For example, the Table 3 productivity regressions do not control for differences in the attributes or complexity of a plant's principal product, and thus the adoption of new CNC machines might reduce setup-times more for more complicated valve products with more customized features. In this case, adoption of new CNC's would be concentrated among custom valve makers.

We use our survey data to offer some evidence about this possibility. We estimate a probit model for the probability that a plant adopts a new CNC machine between 1997 and 2002. These models include a set of controls along with the variable for the 1997 percent catalog variable, our survey's measure of the extent of custom versus commodity production in 1997.[25] Results from these models are, at best, only suggestive since the sample size is greatly reduced (N=59) due to the limited response to the question on the 1997 percent catalog variable. The results from this CNC adoption model show that 1997 percent catalog variable is not a significant determinant of CNC adoption.

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still be that improvements in the CNC technology matter, but these technological improvements are accompanied by changes in engineering quality.

[24] For a review of alternative treatment effects see Heckman, LaLonde, and Smith (1999) and Heckman (1990).

[25] Other control variables in this CNC adoption equation are the number of shopfloor employees, plant age dummies, unionization, and a dummy for competitiveness which equals one if the plant reported that more than six firms (the median value for this variable) produced a product that competed with the plant's main product. Larger plants and plants with more competitors are more likely to purchase a new CNC machines after 1997 than are other plants. When we re-estimate the model for the larger sample of plants after dropping the 1997 percent catalog variable for which data are often missing, these same patterns are still observed.

It is important to note that these models do not test whether the adoption of IT promotes further customization (that is, whether adoption of new IT after 1997 affects the change in a plant's product customization between 1997 and 2002). Models in the next section test this hypothesis about the effects of new IT investments on subsequent increases in product customization. Before we examine this hypothesis, it is important to address the question of what accounts for the lack of adoption of new CNC's (or other new IT-enhanced equipment) among some valve plants. If the estimated "treatment of the treated" effects reported in Table 3 are reasonable estimates of the reductions in production times that non-adopters would experience, why don't all valve plants make these purchases? One possible reason why some plants might not adopt these technologies is that they may face greater adjustment costs than other plants after they adopt these technologies, perhaps due to an older workforce or a plant layout that is less flexible. Here, these IT investments would still generate the reductions in production times implied by the Table 3 regression coefficients, but the "net returns" (i.e., returns after accounting for adjustment costs) would be less for non-adopters than the adopters.[26] The literature on technology adoption also suggests that some plants delay IT purchases until more sophisticated machinery is available because IT prices keep falling and IT capabilities keep improving. In this case, the current non-adopters would actually experience bigger reductions in production times when they adopt because they will be implementing superior technologies. Still, we reiterate that the safest conclusion is that the Table 3 regressions provide evidence of sizable and significant "treatment of the treated" effects. At a minimum, reductions in production times after the adoption of IT-enhanced production equipment are large among those plants that purchased this capital.

VII. Information Technology and Product Customization

For at least two reasons, estimates in Table 3 may understate the overall gains from IT. First, these models only consider reductions in production times on a plant's main product and the new IT investments could reduce production times on other products as well. Furthermore, as the model in Section III implies, new IT is also valuable because it allows plants to design and make new valves that are more complex. The empirical models in this section assess whether product customization rises after plants invest in new information technologies (H3).

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[26] A substantial literature emphasizes that adjustment costs play a large role in the adoption of new technologies (Bresnahan and Greenstein, 1996; David, 1986; Rose and Joskow, 1990; Karshenas and Stoneman, 1993; Stoneman, 1983).

Trends in Product Customization in the Industry

Unlike the analysis in Table 3 of changes in production time which refer to the plant's main product, changes in product customization refer to the range of products made in plants and is therefore a plant-level analysis. We measure changes in customization using survey information on whether the plant increased, decreased or experienced no change in the percent of customer orders that were directly from its catalog products with no design change between 1997 and 2002. Decreases in orders of catalog products reflect an increase in customized production. In the full sample, 62.5% of respondents report no change in the percentage of orders directly from catalog. 13% report an increase in catalog orders, and almost twice as many plants, or 24.5%, report a decline in catalog orders. The analysis to follow investigates whether decreases in production of catalog orders, and thus increases in customized production, are concentrated among plants that invested in different kinds of IT-enhanced production technologies.

IT Adoption and Changes in Production of Customized Products

Table 4 reports the results of four models that express changes in the percent of products coming directly from the plant's product catalog during the 1997-2002 time period as a function of IT adoption. In these multinomial logit models, the dependent variable measures three categories – plants that experience an increase in the percent catalog measure between 1997 and 2002, a decrease in the percent catalog measure, and the (omitted) category of plants with no change in percent catalog.

Whether the IT variables are entered separately (columns 1-3 models) or jointly (column 4), the results are similar. First, plants that adopt CNC machines are more likely to experience a decrease in the percent of customer orders that come directly from their catalogs (line 1). This result concerning the relationship between CNC adoption and a move to more customized production support the predictions of the theoretical framework in Part III. The adoption of new CNC machines reduces setup time in all specifications in the Table 3 analysis, consistent with hypothesis H2. Since setup costs are a larger fraction of unit costs for customized products, the reduction in unit costs due to a reduction in setup time is greater for customized products than commodity products. Therefore, the adoption of new CNC machines also results in an increase in the production of customized products (H3).

Second, the adoption of 3D-CAD technology which facilitates the design of more customized valve products is also, not surprisingly, associated with a decline in catalog production (line 2). While this result is expected, note that the introduction of 3D-CAD need not necessarily lead to an increase in customization if the impact of 3D-CAD is to reduce design to simple machine instructions which in turn enables actual fabrication to be done elsewhere. The results in Table 4, however, clearly show that in the valve manufacturing industry, the introduction of 3D-CAD facilitates an increase in customization.

Finally, the adoption of FMS technology is shown to have a negative relationship with the probability that a plant is in the "percent catalog down" category. While one might expect that the coordination of multiple CNC machines made possible by FMS adoption could promote the production of more customized valve products, plants that adopt FMS technology are less likely than other plants to reduce their sales of catalog products. In considering this pattern, it is worth noting that the results in Table 3 concerning the effects of FMS adoption on setup time are ambiguous and depend on the model specification. In contrast, all model specifications show setup times declining after plants begin using higher quality CNC machines. If FMS adoption does not reduce setup times as new CNC machines do, then the theoretical reason to expect that FMS adoption would lead to an increase in customization is less clear. Also, the Table 3 results do consistently show that FMS adoption reduces product runtimes. Depending on overall demand for valve products and the relative demand for catalog versus non-catalog products that FMS adopters face, these plants may increase production after they experience improvements in runtimes and this increased production could be concentrated among catalog products.

VIII. Information Technology, Worker Skills and HRM Practices

A large literature now considers the effects of new computer technologies on worker skills. This section explores this relationship in our sample of valve manufacturers, as well as the relationship between the adoption of new technologies and new HRM practices.

IT and Operators' Skill Requirements

The data on the adoption of new IT in this study's intra-industry sample permits a different kind of test of the relationship between businesses' IT investments and worker skills than is generally available in existing research. Industry-level studies typically measure skill by the percentage of an industry's workers (or labor costs) who are non-production or white collar workers. These studies measure technology by expenditures on computing equipment or estimates of the computer capital stock for the industry.[27] Several establishment-level studies also examine the relationship between IT and demand for skilled workers (Dunne and Schmitz, 1995; Doms, Dunne and Troske, 1997), and while these studies use detailed measures of technology such as the use of computer-automated design or flexible manufacturing cells, they also measure worker skill by the share of production workers in the plant's labor force or the education level of the plant's workers. The conclusion from these studies is that there is a positive correlation between the use of advanced technologies and proportion of white-collar workers in an industry or the proportion of non-production workers in establishments, although these relationships are often not evident in longitudinal analyses. The detailed data in our survey enable us to address a somewhat different question. Our survey asks about the importance of specific skills within the narrowly defined occupation of machine operators. Therefore, the analysis here considers whether skill requirements change within this narrowly defined group of high-school educated workers after the introduction of IT and not whether an industry or plant workforce now has a larger proportion of white-collar employees.[28]

Table 5 reports results from five separate probit models where the dependent variable equals one if the plant reports that a given skill became more important for operators over the 1997-2002 period. We collected data on five types of skills for machine operators: math skills, computer skills, skills for programming machine operations, problem-solving skills, and engineering knowledge. The survey items ask respondents whether each of these skills has become more important since 1997, less important, or is still equally important. As the means at the bottom of each column indicate, a majority of plants report that each of these skills became more important.[29] The models include variables for the adoption of new IT over this period along with controls. The results are straightforward. These models consistently show that it is primarily the purchase of new CNC's – the central production technology in the industry – that is associated with many skills becoming more important. As described in Section II, the new fusion controlled CNC machines require more sophisticated programming, engineering and problem-

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[27] As examples, Berman, Bound and Griliches (1994), Berndt, Morrison and Rosenblum (1994), and Autor, Katz and Krueger (1998) find a positive correlation between increases in computer investment and increases in the share of skilled labor within an industry.

[28] In our sample of valve plants, the educational requirement for machine operators is primarily a high school diploma (71%) or some high school (9%). Only 4% of the plants required a certificate from a technical school and 5% required an apprenticeship. Nine percent of the plants had no educational requirement for their operators.

[29] The corresponding values for "decreased in importance" are Math: 0.16; Computer: 0.02; Programming, 0.07; Problem-Solving, 0.07; and Engineering Knowledge, 0.12.

solving skills to program complicated valve devices and then to trouble-shoot and re-program after the first prototype valve device is produced and tested. Consistent with this example, the results in Table 5 show that plants that purchase a new CNC also report an increased demand for programming and computer skills, engineering knowledge, and problem-solving skills.

Data on within-plant employment shifts corroborate the conclusion that skill demand has risen in relative terms. We asked plants for the number of CNC operators in 1997 and 2002 and the number of total shopfloor production workers. Among plants that purchased new CNC machines during this period, the number of CNC operators went up by an average of one CNC operator and the ratio of CNC operators per machine held constant at 1.4.[30] Furthermore, among those plants that purchased new CNC machines, the number of other "non-CNC" production workers (i.e., total shopfloor production workers minus CNC operators) fell by 14 workers per plant, and thus the ratio of Other Production Workers to CNC machines fell by 13 per machine to 7 per machine. The reason for this decline is that when a plant purchased a new CNC machine it took multiple older machines out of operation and thus significantly lowered the demand for non-CNC operators.[31] In contrast, the plants that did not purchase new CNC machines saw no significant change in their numbers of CNC operators or of non-CNC operators.[32]

Managers offer a straightforward interpretation of these results related to skill demand. When plants purchased new IT-embedded CNC machines, they changed their demand for skills among their machine operators. These plants no longer demanded the routine machining skills that operators used on older-vintage CNC machines or non-CNC machines. Their investments in IT that is embedded in new CNC's substituted for routine machining skills, and the number of operators fell. IT did not substitute for the most highly skilled: the number of CNC operators was unchanged per machine. Thus, demand for the more skilled CNC operators rose in relative terms, and moreover, the nature of the skills changed, requiring deeper levels of engineering,

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[30] Our theoretical model assumes one operator per machine, and the 1.4 ratio confirms this, given multiple shifts of workers running machines in some plants. Note that the mean number of CNC operators is 25 in 2002 relative to the total shopfloor workers of 96. The data on the change in number of CNC operators has a sizable number of missing values because the sample size falls to 113 plants for those who answered the question on number of CNC operators in 1997. However, this subsample of respondents does not differ from the entire sample in terms of the percent of shopfloor employees who are CNC operators or in terms of its plant size.

[31] We focus on numbers of workers per CNC machine because we did not obtain data on the number of manual machines in operation in 1997. Thus, when the number of non-CNC operators per CNC machine falls over time, we presume it is because, as our interviews suggest, new CNC machines often replaced multiple older machines.

[32] Regression analysis confirms that plants that purchased new CNC machines from 1997 to 2002 are the plants that experienced highly significant losses in non-CNC operators, even with controls for other technology, the number of shopfloor workers, and unionization rates.

programming, and problem solving skills among the CNC operators and less routine machine skills.

This interpretation of the empirical results – that new IT investments increase the demand for non-routine problem solving skills but decrease the demand for routine skills – is consistent with the findings of previous case study and empirical research. For example, Levy and Murnane (2004) report that skill demand increases with increases in computerization due to the give-and-take problem solving that is required with new product design and manufacturing for the case of circuit board design and production. These non-routine cognitive skills are likely to reflect expert thinking (or the expert recognition of subtle patterns too complex for computers to identify) or complex communications between experts (such as communications between designers and customers) to solve problems. Autor, Levy, and Murnane (2003) find that increased computerization has been accompanied by an increase in the demand for non-routine cognitive skills. Analyzing data on the U.S. labor market, Autor, Katz, and Kearney (2005, 2006) show that during the past fifteen years of rapidly falling computer prices, wages and employment have increased dramatically in the polar ends of the wage distribution: wages rose in occupations that employ the most highly skilled workers whose skills complement computerization, and wages rose in very low-skilled jobs for which there is no computer substitute. In contrast, employment and wages among median-wage workers have not grown over time, consistent with an interpretation that computers are more likely to substitute for the routine tasks these workers do. Our data look at a manufacturing industry that employs approximately median wage workers, and we conclude that job losses in this industry are occurring among those production workers with routine skills, but those workers possessing non-routine problem-solving skills complement the increased computerization of the industry and are not suffering employment losses within plants.

IT and HRM Practices

While the role of HRM practices is not incorporated explicitly in our model, a number of studies (Bresnahan, Brynjolfsson and Hitt, 2002; Black and Lynch, 2001; Bresnahan and Greenstein, 1996; and Mendelson, 2000) find a link between the adoption of new computer technologies and the adoption of new types of work practices. Table 6 analyzes the relationship between the adoption of IT and HRM practices in the valve-manufacturing industry during the 1997-2002 time period. We study the adoption of three HRM practices: teams, shopfloor meetings for information sharing, and training in technical skills. These policies had already been adopted by 34%, 60% and 49% of our sample of valve plants by 1997. Still, during the 1997-2002 that we analyze here, an additional 30%, 35% and 21% of the sample adopted these HRM practices for the first time. In Table 6, we report results from three separate probit models in which the dependent variables measure the adoption of these practices. The samples for these three probit models include those observations that did not have the given practices as of 1997, and the dependent variable equals one for those plants that adopt the given practice by 2002.[33] The results in Table 6 show a positive and significant correlation between the adoption of IT and HRM, but as in the Table 5 models that investigate the relationship between worker skills and IT adoption, it is the adoption of new CNCs in the period that is correlated with the adoption of these new HRM practices. When a plant makes a new investment in more technologically advanced versions of the central CNC production technology, it is also more likely to institute technical training programs, problem solving teams, and shopfloor meetings. These findings are consistent with the Table 5 results regarding the impact of computerization on skill demand. Computers take care of the routine tasks that were done by machinists in the past, but machinists continue to be needed to solve problems, both individually and in teams. In addition, these machinists must be trained in the use of the specific computer software so that they can undertake the non-routine problem-solving that is a key part of their job.

IX. Conclusion

The central proposition of this study is that new information technologies adopted in the 1990s changed manufacturing businesses in fundamental ways. Business strategies favor more customized production, and work processes are carried out by more skilled operators under new HRM practices. Firms in the U.S. increasingly shifted to the production of customized products, and this shift in strategy occurred because the falling cost of information technologies produced productivity gains, especially faster machine setup times, that favored the production of customized products instead of commodities. Theorists have previously made this point but data have been lacking to test the proposition. Testing this proposition requires the collection of unique data – data that identifies what IT really means in the context of the production process, data on the productivity gains from IT at the process level, and data on product customization.

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[33] The means of the dependent variables in Table 6 are the percentage of the plants that had not adopted the practice by 1997 but adopted the practice by 2002.

Unique data on specific IT investments, productivity measures, worker skills and work practices from valve-making plants map out a very clear pattern of findings that is consistent with the study's main proposition and that pinpoints some of the detailed mechanisms that permit this change in business strategy. In the valve-making industry, new computerized technologies raise productivity by lowering the time it takes to setup the production line for new product runs, and also lowering the runtime and the inspection time during production. We also document that IT adopters increase the customization of their products, and the efficiency gains due to new IT investments offer an explanation for this change in business strategy. Lower setup times increase the efficiency and lower the cost of customized production. Plants that adopt new IT experience an even broader set of organizational changes as these plants exhibit an increase in the demand for technical and problem-solving skills and also adopt new work practices that support these skills. In sum, the falling price of an input – the price of computerized capital – changes not only the quantity of that input and related inputs, but it also changes a business's competitive strategy as well as the skill requirements and work practices needed to implement the new strategy. Once a business invests in new IT-based production machinery and installs the equipment on the factory floor, it will be changing the fundamental nature of what it does and how it does it.

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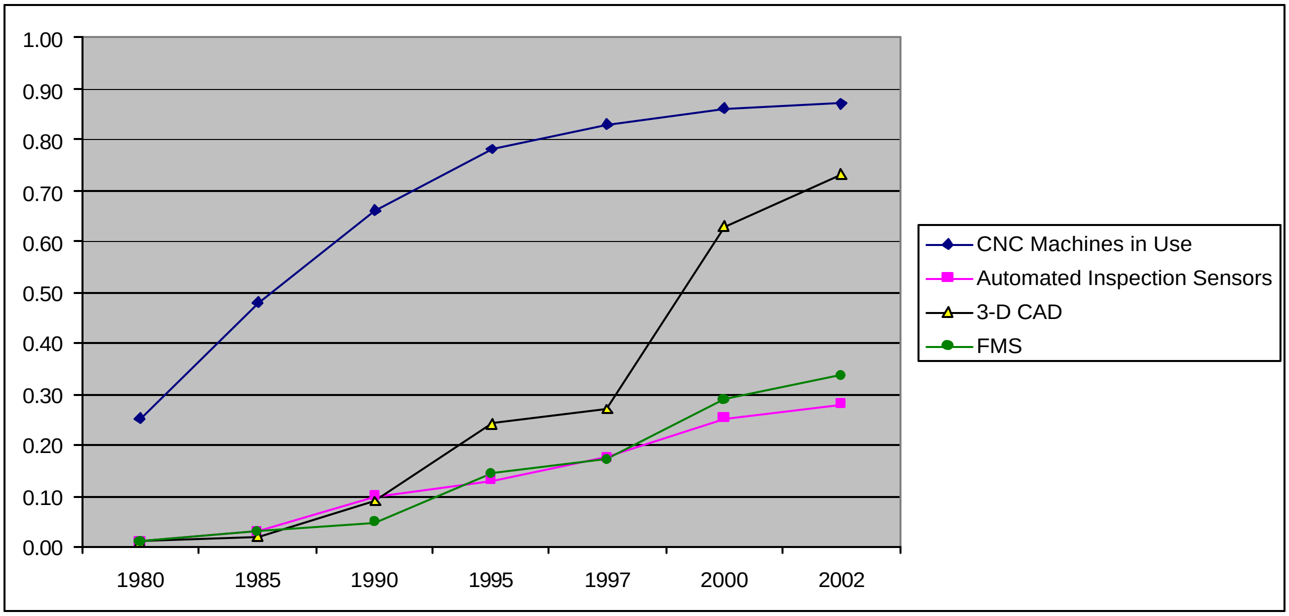
Figure 1

Proportion of Plants with Computer-Aided Production Technologies



Data source: Personal survey of 212 valve making plants.

Table 1
The Effects of IT on Production Efficiency within One Plant
Dependent Variables: Product-Specific Production Times[a]

Dependent Variable	**Log (Setup time)**	**Log (Setup time)**	**Log (Runtime)**	**Log (Runtime)**
Log("CNC Quality")[b]	-0.876*** (0.048)	-0.903*** (0.051)	-0.602*** (0.046)	-0.632*** (0.048)
Yearly Time Trend		0.005 (0.003)		0.003 (0.003)
R^2 - within	0.42	0.43	0.27	0.29
between	0.68	0.68	0.57	0.56
overall	0.60	0.61	0.48	0.49
N	790	762	790	762
Mean of Dependent Variable	6.15		3.93	
(s.d.)	(0.81)		(1.43)	
Median	6.20		3.82	

[a] Models control for product-specific fixed effects. Setup-time and run-time are measured for each of the 331 products for each time period the product was produced at the plant.

[b] "CNC quality" is measured by the negative of the number of machines used to make the plant's main valve product. A decrease in the number of CNC machines used to produce a given product indicates that the plant has begun using a smaller number of newer, more flexible and capable, CNC machines to make the given product. Thus, in these fixed effects models, the coefficient on "CNC quality" measures the change in production times due to a reduction in number of (newer) CNC machines used to make the product.

Table 2
Changes in Product-Specific Production Efficiency Measures, 1997-2002

Product-Specific Production Efficiency Measures	***Medians***		***Means***		***Mean of Log (2002 Production Time) minus Log (1997 Production Time)***
	1997[a]	***2002***[a]	***1997***[a]	***2002***[a]	
Setup time	3.00	1.50	11.03	6.04	-0.681
Run time	0.25	0.17	10.77	9.32	-0.371
Inspection time	0.17	0.14	1.22	0.84	-0.334
Total time	5.00	3.00	24.08	16.59	-0.488

[a] *In hours.Times pertain to typical time to setup, run, or inspect the given plant's main product.*

Table 3
The Effects of IT and HRM on Production Efficiency, 1997-2002[a]
Dependent Variables: Product –Specific Production Times

Dependent Variable:	Percentage Change in Setup-Time	Percentage Change in Setup-Time	Percentage Change in Runtime	Percentage Change in Runtime	Percentage Change in Inspection Time
	(OLS)	(Median Regression)	(OLS)	(Median Regression)	(OLS)
Log (Change in "CNC Quality")[b]	-0.798*** (0.346)	-0.778*** (0.047)	-0.378* (0.222)	-0.438*** (0.075)	-0.139 (0.222)
Adopted Flexible Manuf. System	0.085 (0.263)	-0.184*** (0.051)	-0.408* (0.238)	-0.191** (0.084)	0.237 (0.221)
Adopted Automated Inspection Sensors	0.014 (0.263)	-0.043 (0.059)	0.257 (0.252)	0.057 (0.092)	-0.884*** (0.446)
Adopted Technical Training	-0.549** (0.217)	-0.549*** (0.050)	-0.432* (0.193)	-0.308*** (0.078)	-0.266 (0.354)
Adopted Teams	0.358 (0.211)	0.014 (0.044)	0.188 (0.175)	0.041 (0.069)	-0.417 (0.338)
Observations	146	146	140	140	151
R^2/Pseudo R^2	0.14	0.12	0.24	0.15	0.10

Huber-White robust standard errors in parentheses.

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

[a] All regressions include controls for age of plants (five age dummies), number of shopfloor workers and dummy for unionization

[b] Change in "CNC quality" is measured by the decline in the number of CNC machines used to produce the plant's main product; or, -(# of CNCs to produce the main product in 2002 - # of CNC's used in 1997). A decrease in the number of CNC machines used to produce a given product indicates an increase in the quality of the CNC machines being used. See Section IV of text for explanation.

Table 4

The Effects of IT on Change in Product Customization, 1997-2002[a]

	(1a)	(1b)	(2a)	(2b)	(3a)	(3b)	(4a)	(4b)
Dependent Variable:	Percent Catalog Up[b]	Percent Catalog Down[b]	Percent Catalog Up[b]	Percent Catalog Down[b]	Percent Catalog Up[b]	Percent Catalog Down[b]	Percent Catalog Up[b]	Percent Catalog Down[b]
Bought New CNC Machine	0.757 (0.600)	1.045** (0.494)					0.797 (0.603)	1.018** (0.521)
Adopted 3D-CAD			-0.249 (0.502)	0.868** (0.396)			-0.246 (0.512)	0.852** (0.423)
Adopted Flexible Manufacturing System					0.361 (0.613)	-2.415** (1.111)	0.360 (0.635)	-2.433** (1.085)
Adopted Automated Inspection Sensors							-1.063 (0.692)	-0.379 (0.612)
Observations	182	182	182	182	182	182	182	182
Pseudo R-squared	0.0872	0.0872	0.0880	0.0880	0.1028	0.1028	0.1406	0.1406

Huber-White robust standard errors in parentheses. *Significant at 10%; ** Significant at 5%; *** Significant at 1%

[a] Regressions include controls for age of plants (five age dummies), number of shopfloor workers, and dummy for unionization

[b] The dependent variable has 3 categories: the *percent catalog down* category includes plants that report that the percentage of customer orders that were valves in the product catalog with no modifications went down between 1997 and 2002; the percent catalog up category includes plants that report that this percentage went up between 1997 and 2002; and the (omitted) category includes plants that reported that this percentage was unchanged between 1997 and 2002. The percent catalog up (down) category identifies plants with decreases (increases) in customized production over this five-year period.

Table 5
The Effects of IT Adoption on Increased Importance of Different Types of Skills[a]
Dependent Variable: Equals One if Skill's Importance Increased Between 1997 and 2002

	(1) Math	(2) Computer	(3) Programming	(4) Problem-Solving	(5) Engineering Knowledge
Bought New CNC Machine	0.121 (0.087)	0.142* (0.082)	0.275*** (0.089)	0.137* (0.084)	0.185** (0.086)
Adopted 3D-CAD	-0.083 (0.077)	0.104 (0.067)	0.066 (0.079)	-0.102 (0.074)	-0.072 (0.079)
Adopted Flexible Manufacturing System	0.274*** (0.083)	0.092 (0.081)	-0.057 (0.106)	0.026 (0.092)	0.064 (0.101)
Adopted Automated Inspection Sensors	0.026 (0.116)	0.024 (0.102)	0.053 (0.116)	-0.066 (0.110)	0.168 (0.108)
Pseudo-R^2	0.07	0.07	0.12	0.05	0.06
Sample Size	201	200	196	200	200
Means	0.57	0.71	0.53	0.68	0.52

Huber-White robust standard errors in parentheses.
*Significant at 10%; ** Significant at 5%; *** Significant at 1%

[a] Probit coefficients evaluated at the mean are shown . Regressions include controls for age of plants (five age dummies), number of shopfloor workers, and dummy for unionization

Table 6
The Effects of IT Adoption on the Adoption of New HRM Practices, 1997-2002[a]
Dependent Variable: Equals One if Plant Adopted the HRM Practice Between 1997 and 2002

	(1)	(2)	(3)
Dependent Variable[b]:	Teams	Shopfloor Meetings	Technical Training
Bought New CNC Machine	0.310*** (0.092)	0.237* (0.129)	0.258*** (0.096)
Adopted 3D-CAD	0.079 (0.098)	0.067 (0.099)	0.167 (0.106)
Adopted Flexible Manufacturing System	-0.043 (0.130)	0.027 (0.126)	0.179 (0.124)
Adopted Automated Inspection Sensors	0.065 (0.161)	0.168 (0.113)	0.280* (0.173)
Observations	132	93	111
Log Likelihood	-74.52	-52.79	-54.61
Pseudo R2	0.172	0.0853	0.247
Means	0.42	0.69	0.36

Huber-White robust standard errors in parentheses.
*Significant at 10%; ** Significant at 5%; *** Significant at 1%

[a] Probit coefficients evaluated at the mean are shown . Regressions include controls for age of plants (five age dummies), number of shopfloor workers, and dummy for unionization

The samples for these probit models include those plants that did not have the given practices as of 1997, and the dependent variable equals one for those plants that adopt the given practice by 2002.