HOW DOES INFORMATION TECHNOLOGY AFFECT PRODUCTIVITY? PLANT-LEVEL COMPARISONS OF PRODUCT INNOVATION, PROCESS IMPROVEMENT, AND WORKER SKILLS*

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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, 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 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 economywide studies on the timing and industry location of IT investments suggests that new IT may be responsible for a substantial part of the accelerated productivity growth since the mid-1990s (Oliner

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and Sichel 2000; Jorgenson, Ho, and Stiroh 2005). 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 analyzed 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, eliminates 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 the 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 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.

1. For other micro-level studies concerning the effects of new computer technologies on productivity, see Athey and Stern (2002), Brynjolfsson and Hitt (2003), and Hubbard (2003). Examples from the extensive literature on the effects of computer technologies on worker skills are Dunne and Schmitz (1995), Doms, Dunne, and Troske (1997), Autor, Katz, and Krueger (1998), Caroli and van Reenen (2001), Autor, Levy, and Murnane (2003), Dunne, Haltiwanger, and Foster (2004), and Autor, Katz, and Kearney (2005). Black and Lynch (2001) and Bresnahan, Brynjolfsson, and Hitt (2002) present evidence on the link between computer-based IT and new work 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 1990s. In service sector industries such as call centers, hospital emergency rooms, and concert entertainment, 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. While new IT appears to promote customization of products and services in many industries,[2] 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 VII 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 VIII 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, and empirical tests. We first describe the industry's production process and how innovations in

2. For evidence on how the Internet has increased product variety, see Brynjolfsson, Smith, and Yu (2003).

IT have changed the process. The section concludes with an analysis of detailed performance and technology data from one plant.

II.A. Information Technology 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. 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.

Valve manufacturing today 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 into the machine's operating software.[3] The *CNC controller* box, the main IT element of these machines, tells the CNC machine exactly how to cut and reposition the steel. CNC machines are now in widespread use in the industry. Substantial information-processing capabilities are now embedded directly into new CNC controllers. We describe three of the most important IT-based improvements in CNCs in recent years—fusion control, greater axis capabilities, and more efficient software—to illustrate the effects of new IT on the production process.

"Fusion control" refers to new technology that has made the programming that controls CNCs more conversational and simpler to complete and execute. This technological improvement speeds up the process of programming all the machining tasks, automates the process of getting the right cutting tools into the CNC's tool rack, and reduces the time it takes to "qualify" a job in

3. CNC machines were predated by numerically controlled (NC) machines in which early computer programming technologies controlled the machine run by run, and by manually operated machines. 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.

a test run to identify and correct programming errors. These improvements lead directly to reductions in machine *setup times.* Fusion control technology was new to CNC machines in 1998 and was standard in new CNC machines by 2003. Newer CNC machines also have improved "axis capabilities." Newer five-axis CNC millers can machine a valve component on five different angles or axes in one "fixturing" operation, compared to a previous limit of three axes in earlier CNCs. By eliminating the need to reposition valves for cuts on fourth or fifth axes, this technology directly reduces machine *run times*. Finally, newer CNCs make use of more efficient software. Newer programs allow CNC machine tools to create smooth curves on a valve component, called "curve interpolation," rather than approximating curves using a large number of linear cuts. Software advances also permit more sophisticated machining operations with smaller programs that are easier to edit and troubleshoot, 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 the time it takes to complete a given cutting or drilling task. Rather, newer CNC machines are more flexible and 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 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. These observations are important for construction of the CNC technology variables used in the empirical work in this study. Because IT is completely embedded in new CNC machines, simple inspections of machines would not reveal these technological advances. Managers stated that a decrease in the number of machines used to produce a given product would always reflect an increase in degree of computerization for newer versus older CNC machines and was also relatively simple for managers to identify. Thus, in empirical analyses 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*.[4]

4. 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,

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 and reduces the number of tool changes that are required as the controller allocates jobs across different CNC machines, thereby reducing run time. The computerized instructions that coordinate machining tasks across different CNC machines can also reduce the time it takes to complete setup tasks.

Finally, our interviews identified IT advances that reduce the *inspection time* in the quality control 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 that 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 operates the probe and checks measurements against specifications without any operators.

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 emphasized two operational imperatives for remaining competitive in this industry.

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 either were unavailable or could not be linked back to plants in the survey we developed.

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 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.

II.B. Econometric Case Study Evidence: The Effects of Information Technology 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 290 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 that the 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.[5] Based on these arguments from operators and managers at the plant, we define the technology variable "CNC Quality" as the negative of the logarithm of the number of CNC machines used to produce the product and enter it as a determinant of production times.[6] Because these models control for product-specific fixed effects, the coefficient on the CNC Quality variable in these models estimates 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 execute all of the tasks that a larger number of machines formerly 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 are also easier to set 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 during the plant's history. When a product was produced prior to 1999, observations on the product from the earlier years are included in this panel data set. Seventy-five percent of the observations are for 1999–2003, and the remainder of the observations comes from the years between

5. In our larger survey data set that is described below, we find that plants that reduced the number of machines they used to produce a given product between 1997 and 2002 were 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.

6. Because a smaller number of machines used to make a given product indicates the use of higher-quality CNCs, we take the negative of the logarithm of the number of machines, so that higher values of this CNC quality variable would be associated with lower production times whenever the use of a smaller number of (newer) machines reduced production times.

TABLE I
THE EFFECTS OF IT ON PRODUCTION EFFICIENCY WITHIN ONE PLANT[a,b]

Dependent variable	Log (setup time)	Log (setup time)	Log (run time)	Log (run time)
"CNC quality"[c]	−0.937***	−0.957***	−0.623***	−0.699***
	(0.079)	(0.082)	(0.057)	(0.066)
Year dummies[d]	No	Yes	No	Yes
R^2	0.47	0.52	0.29	0.39
Mean of dependent	6.197		3.951	
variable (s.d.)	(0.811)		(1.445)	
Median	6.234		3.855	

[a]Models control for product-specific fixed effects. Newey-West robust standard errors with corrections for heteroscedasticity and autocorrelation in parentheses.

[b]Dependent variables: product-specific production times ($N = 720$). Sample description: Each observation in this sample is a record of the production times for a specific valve product made in one valve making plant. The record reports setup time, run time, and number of CNC machines for the given product run. The sample includes any valve product the plant produced during the period 1999–2003, a total of 290 separate valve products. Of the observations in this sample, 75.3% come from this 1999–2003 period. The sample also includes longitudinal data for these products prior to 1999 if the plant produced the product in earlier years. The number of product records from these earlier years ranges from one observation in 1978 to nineteen observations in 1998. Of the products, 70.3% are observed twice; 18.3% are observed three times; and the remaining 11.4% are observed from four to eight times.

[c]The quality of CNC machines used to make a given product is higher when the plant uses a smaller number of (technologically more capable) CNCs to make the product. A reduction in the number of machines to make the same product is an increase in machine quality. Thus, "CNC quality" is measured as $(-1) \times$ ln(number of machines used to make the valve product). In these fixed effects models, the coefficient of this "CNC quality" variable measures the within-product change in production times due to a reduction in the number of CNC machines used to produce the product. If using a smaller number of higher-quality CNC machines reduces production times, then the coefficient on this CNC quality variable is negative.

[d]Twenty-five-year dummies are included in the models in columns (2) and (4).

*Significant at 10%. **Significant at 5%. ***Significant at 1%.

1978 and 1998. Overall, this data set contains 790 observations for 290 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 run time for each machine used.

When these production time models with controls for product-specific fixed effects are estimated, the results in Table I are obtained. An increase in this CNC quality index (which equals the negative of the logarithm of the number of CNC machines used to make a product) is associated with significantly lower 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% 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 9.4% (Table I, column (1)). For the full sample, the average number of machines used to make a product is 6.3 machines. The average change in the number of machines used to make a valve product in the full sample is −0.73 machines (or 11.6% of the average number of machines), and for the subsample of products that reduced the number of CNC machines, the average change was −2.7 machines (or 42.9% of the average number of machines). Reductions in the numbers of CNC machines used of these magnitudes would be associated with 10.9% and 40.2% reductions in setup time, respectively.

The effects of an increase in this CNC quality index are also sizable in the run time equation. A 10% decrease in machines (increase in CNC quality) reduces run time by 6.2% (Table I, column (3)). However, because typical run times are much shorter than setup times (median setup and run times are 510 and 47 minutes, respectively), the most important quantitative gains are in setup time reduction. Note that the inclusion of a set of year dummy variables in the column (2) and (4) models has little effect on the estimated effects of the CNC quality variable, perhaps as a result of the fact that the time series that we have for most valve products are very short.

While the estimates from the product-specific regressions in Table I 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 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 I regressions reflect the average increase in quality of the CNC machines purchased. Second, the most complicated products, which 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, the introduction of CNC machines has large significant effects on production times.

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 for the Impact of Information Technology

Valve manufacturing is a batch process. Products in many other manufacturing industries are also made in batches. Each new compound in chemical production, each different 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 those of 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 adjustment 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 smaller than the 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 $B_{\mathrm{cu}} < B_{\mathrm{co}}$. 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:

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

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

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

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

where $\pi \equiv$ profits
$S_j \equiv$ hours to setup machine to run a batch of product; $j = \mathrm{co}, \mathrm{cu}$
$R_j \equiv$ hours to run each unit of product; $j = \mathrm{co}, \mathrm{cu}$
$I_j \equiv$ hours to inspect each unit of product; $j = \mathrm{co}, \mathrm{cu}$
$D_{\mathrm{cu}} \equiv$ added cost of design and promotion for customized products only
$B_j \equiv$ average batch size (number produced per scheduled batch); $j = \mathrm{co}, \mathrm{cu}$
$N_j \equiv$ number of batches of product j; $j = \mathrm{co}, \mathrm{cu}$
$M_j \equiv$ materials costs per unit; $j = \mathrm{co}, \mathrm{cu}$
$P_j \equiv$ average price of product j; $j = \mathrm{co}, \mathrm{cu}$
$w \equiv$ wage rate
$r \equiv$ rental cost of capital
$P_{\mathrm{IT}}\mathrm{IT} \equiv$ 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 functions of IT-imbedded capital and other variables,

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

$$(4) \qquad R_j = f^{R}(\text{IT}_j^{R}, X), \text{ for } j = \text{co, cu}$$

$$(5) \qquad I_j = f^{I}(\text{IT}_j^{I}, X), \text{ for } j = \text{co, cu,}$$

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 equation (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, run time, and inspection time should fall when plants adopt IT machinery relevant to these processes. Thus, in equations (3)–(5), we assume that $\partial \text{S}_j/\partial(\text{IT}) < 0$, $\partial \text{R}_j/\partial(\text{IT}) < 0$, and $\partial \text{I}_j/\partial(\text{IT}) < 0$. 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 toward 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 (∂(unit costs)/$\partial S_j = 1/B_j$) and $B_{\text{cu}} < B_{\text{co}}$. Given this falling cost of customized products relative to commodity products, plants increase their production of customized products, all else constant.[7] Even if

7. Thus, firms move toward customized production if they are price takers and product prices are unchanged. In their model, Milgrom and Roberts (1990) make

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 will increase their customized production if customized products sell at higher prices.[8] Finally, another reason that IT will induce a move toward greater production of customized products is that some advances in IT, such as computer-aided design, lower design costs that, 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.[9] 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 run time), 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—that is, customized products that have higher setup time relative to total run time—which would increase skill demand, thereby offsetting the first influence of IT. The net effect of these two factors cannot be predicted. A third factor not explicitly incorporated into 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 the cutting tools from the tool fixture and moving the tools

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the assumption that their multiproduct 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 or nonlinear adjustment costs for changing the plant size or for finding new customers. Similarly, we are modeling the short-run decision to become more customized, and in the short run, the costs of significantly increasing plant size or seeking large numbers of new customers are accelerating, thereby limiting the increase in the optimal amount of customized product that is produced.

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

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

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 is increasingly done automatically by the newer CNC machines, while the demand for nonroutine problem-solving skills that are required to set up, monitor, and correct the new sophisticated CNC machines appears 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 four hypotheses in the empirical work:

H1. 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.

H2. New IT promotes product customization and innovation. 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.

H3. IT adoption may increase (or decrease) skill demand.

H4. 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 customers. 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 twentieth 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 (2001) 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 lead to greater product customization and variety, and this may also lead to an increase in demand for skills among shop floor operators in this manufacturing industry.[10]

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 I. 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.

IV.A. The Sample of Valve Industry Plants

After conducting the field research, we designed, pretested, and conducted a customized industry survey in 2002.[11] To identify the population of U.S. valve-making plants for this 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

10. 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.

11. The Office for Survey Research at the Institute for Public Policy and Social Research at Michigan State University conducted the pretests 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.

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.[12] Empirical results in the study are based on the responses from these 212 valve-making plants.[13]

IV.B. 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)?

IV.C. Product Customization Measure

Increases in customization imply changes in the number of products a plant makes. Unlike the process efficiency measures, which pertain to one product, this is a *plantwide* measure of the range of products a plant makes. Based on discussions with

12. 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.

13. Nonrespondents do not differ greatly from the survey respondents in terms of sales and number of employees (the only two variables available for the nonrespondents), according to values of a chi-squared test. For sales, the chi-squared = 10.81; with five degrees of freedom corresponding to the five sales categories, the critical value at the 5% significance level is 11.07. For employees, the chi-squared = 12.55; with eight degrees of freedom corresponding to the eight categories for number of employees, the critical value at the 5% significance level is 15.51. 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.

managers, we measure the extent to which plants customize products for the specific needs of customers with the question

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

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 percentage 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*.

IV.D. 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.[14]

The remaining IT variables are plantwide variables.

14. 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 their main products 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.

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?

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.

V. 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.

V.A. Trends in the Adoption of IT

Figure I 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-fourth 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 nonexistent in the industry in 1980 and can now be found in

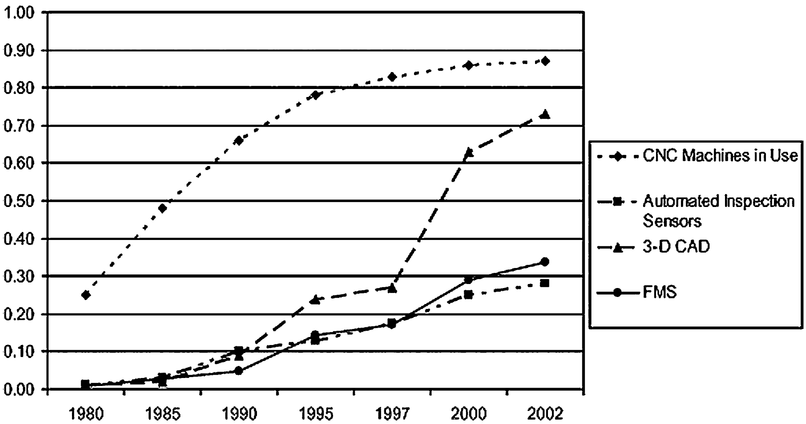

FIGURE I
Proportion of Plants with Computer-Aided Production Technologies
Data source: Authors' survey of 212 valve making plants. See Section IV.

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 that 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.[15]

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% of the plants purchased at least one additional CNC machine between 1997 and 2002. Moreover, our study's measure of CNC quality—the number of CNC machines used to produce the plant's main product—also changed in this period. The mean (and median) number of machines used to produce a plant's main product was 6.03 (4) in 1997 and declined to 4.87 (3) in 2002.

15. 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 I for IT adoption will overestimate the diffusion of these technologies if plants that exited the industry are less likely to have introduced them.

TABLE II
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

Data source. Authors' survey of valve manufacturing plants. See Section IV.
[a] Production times are measured in hours and pertain to the typical time to set up, run, or inspect the product that the plant produced the most in the period 1997–2002. Setup time is measured per batch while run time and inspection time are per unit to adjust for differences in batch sizes across plants. Total production time is therefore the time it takes a plant to produce a one-unit batch. The difference between median and mean production times is due to a very small number of observations with large production times.

Among the subsample of plants that did reduce the number of machines used to make the main product, the average decline was 3.3 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.

V.B. Trends in Production Times

Table II 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 times 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 period 1997–2002, 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 I and Table II 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)

$$\Delta \ln(\text{ProductionTime}) = a + \mathbf{b}_1(\mathbf{\Delta\ NewTechnology}) + \mathbf{b}_2\mathbf{X} + e_1.$$

The dependent variable in (6) is log(2002 Production Time) minus log (1997 Production Time)—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 **(Δ 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 minus one times the log 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, the union status, the plant size measured as number of shop floor workers, and a measure of the change in the number of competitors making a similar product. 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 distribution for each of these production time variables, as well as the change in the production times, has several large outliers,[16] we estimate

16. 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% of the sample has a value of zero and 5% has a value of less than −2.5. In the case of the percentage change in run time, the range is from −4.787 to 3.612 with a mean of −0.354 and a median of −0.182; 38% of the sample has a value of zero and 5% of the sample has a value of 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.

equation (6) models when possible with both OLS and median regressions.[17]

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

The regression results reported in Table III are consistent with hypothesis H1 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 in a given stage of the machining process reduces production times in that stage significantly.

The variable "Change in CNC Quality" is minus one times [ln(number of CNC machines used to produce the plant's main product in 2002) minus ln(number of CNC machines used to produce the plant's main product in 1997)]. If using a smaller number of higher quality machines in the later time period yields a reduction in production times, then the coefficient on this "Change in CNC Quality" variable will be negative. The adoption of higher-quality CNC machines reduces setup time (columns (1) and (2)) and run time (columns (3) and (4)). Both of these results for this industrywide sample of valve plants mirror the results from the econometric single-plant case study reported in Section II. Run time 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 of results in Table III 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.*[18]

17. Median regressions for the change in inspection time are not estimated, as these models do not converge.

18. We also re-estimated the Table III models, including a variable for the adoption of new 3D-CAD technology. When we described advances in valve-making technologies in Section II, we hypothesized that this valve design technology should affect product customization and design times rather than production times. Consistent with this expectation, the adoption of 3D-CAD technology has no significant effects on any of the production time variables.

TABLE III
THE EFFECTS OF IT AND HRM ON PRODUCTION EFFICIENCY, 1997–2002[a]

Dependent variable	Percentage change in setup time (OLS)	Percentage change in setup time (Median regression)	Percentage change in run time (OLS)	Percentage change in run time (Median regression)	Percentage change in inspection time[c] (OLS)
Log (change in "CNC quality")[b]	−0.805***	−0.731***	−0.383*	−0.432***	−0.085
	(0.340)	(0.041)	(0.230)	(0.062)	(0.234)
Adopted flexible manuf. system	0.096	−0.162***	−0.424*	−0.168***	0.234
	(0.265)	(0.045)	(0.242)	(0.067)	(0.220)
Adopted automated inspection sensors	0.037	−0.054	0.289	0.109	−0.915*
	(0.272)	(0.050)	(0.278)	(0.077)	(0.450)
Adopted technical training	−0.529**	−0.597***	−0.452**	−0.284***	−0.256
	(0.216)	(0.044)	(0.201)	(0.061)	(0.372)
Adopted teams	0.343	0.026	0.240	0.093	−0.392
	(0.231)	(0.039)	(0.190)	(0.055)	(0.358)
Observations	141	141	134	134	145
R^2/pseudo R^2	0.14	0.11	0.25	0.16	0.12

Data Source. Authors' survey of valve manufacturing plants. See Section IV.

[a] Dependent variables: log(2002 production time) – log(1997 production time). All regressions include controls for age of plant (five age dummies), number of shop floor workers, a dummy for unionization, and two dummy variables indicating whether the number of competitors that produce a product that competes with the firm's main product went up or down. Huber-White robust standard errors are in parentheses in the models shown in columns (1), (3), and (5).

[b] Log (change in "CNC quality") is measured as $(-1) \cdot$ [ln(number of CNC machines used to produce the plant's main product in 2002) – ln(number of CNC machines used to produce the plant's main product in 1997)]. If using a smaller number of higher-quality machines in the later time period yields a reduction in production times, then the coefficient on this log(change in CNC quality) variable will be negative.

[c] Median regression model for change in inspection time did not converge.

*Significant at 10%. **Significant at 5%. ***Significant at 1%.

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. According to the means of the production time variables reported in Table II, setup times in 1997 were the largest component of overall production time, accounting for almost one-half of overall production time. The estimated savings in setup times after the adoption of more advanced CNC machines, shown in columns (1) and (2) of Table III, are sizable. The regression in column (1) shows that a 10% reduction in the number of machines used to make the plant's main product (i.e., an increase in the quality of the CNC machines used) reduces setup time by 8.1%. The average change in the number of machines used to make a valve product in the full sample is −22%, and for the subsample of plants that experienced an improvement in CNC quality, as measured by a decrease in the number of machines after 1997, the average change in machines is −63%. Reductions in the numbers of CNC machines used of these magnitudes would be associated with 17.7% and 50.7% reductions in setup time, respectively. Improvements in CNC quality are also associated with reductions in run time, as shown in columns (3) and (4). Using the coefficient in column (3), the average changes in the number of machines for the full sample and the subsample are associated with reductions in run time of 8.4% and 24%, respectively.

Results in Table III also reveal that plants that introduce technical training programs realize an additional reduction in setup times and run times. 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 III demonstrate that *HRM policies designed to improve the specific skills needed to operate new technologies in the plant are in fact the initiatives that are associated with improvements in the speed of machining operations during a given product run*.[19]

19. Unlike others who have found significant interaction terms between IT and HR practices using plant-level productivity measures (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

The Table III results are consistent with the conclusion that new IT equipment improves the efficiency of the production stages in which it operates. Still, these are not experimental data with random assignment of IT across plants. Thus, another possible interpretation is that there may be some unobserved shock that gives managers incentives to introduce new CNCs or other types of IT and also speed up production times, thereby causing a bias on the CNC coefficients.

While the nonexperimental data obviously cannot rule out this type of omitted variable interpretation,[20] the sample and models do have several useful features that require that any such omitted variable(s) must have certain characteristics besides a correlation with both IT adoption and improved production times. First, the carefully drawn intraindustry sample eliminates many sources of unobserved heterogeneity from consideration. Moreover, the longitudinal models also control for the effects of all plant-specific factors, and the estimated effects of the IT adoption variables pertain to three different stages of production within the same plant. Thus, to account for the full set of IT coefficients in Table III, the factor omitted from the analysis that is correlated with both IT adoption and improved production times must also vary over time within plants and have different effects across stages within plants.[21] For example, if managerial quality improves near the time that new CNCs are purchased, then this omitted factor can account for the effect of the CNC variable on changes in setup or run times. However, the improved managerial

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that, at the plant level, the adoption of IT, specifically new CNC machines, and new HRM practices are highly correlated.

20. Even if one only considers the coefficient estimates from the longitudinal first-difference models to be an estimate of a "treatment of the treated" effect—for example, the effect of new CNCs on setup or run times just among those valve plants that adopted new CNCs for its main product—a time-varying omitted variable correlated with IT adoption and production times would still bias the estimated treatment of the treated effect. For a review of alternative treatment effects see Heckman (1990) and Heckman, LaLonde, and Smith (1999).

21. The Table III regressions do not control for differences in the complexity of a plant's principal product. We therefore considered whether product complexity is an omitted variable that is correlated with the adoption of new CNC machines, with new CNCs having larger effects on setup or run times for the more complex products. We estimate a probit model that expresses the probability that a plant adopts a new CNC machine between 1997 and 2002 as a function of the variable for the 1997 percent catalog variable (our survey's measure of the extent of custom versus commodity production in 1997) and the other controls used in the Table III models. While the sample size for this model is relatively small ($N = 52$), due to the limited response to the question on the 1997 percent catalog variable, making results at best suggestive, the 1997 percent catalog variable is not a significant determinant of CNC adoption in this model.

quality must somehow not be relevant to improving performance in the inspection stage, since the CNC variable does not have a significant effect on inspection times.[22]

VI. Information Technology and Product Customization

For at least two reasons, estimates in Table III 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 (hypothesis H2).

VI.A. Trends in Product Customization in the Industry

Unlike the analysis in Table III of changes in production time that affect the plant's main product, changes in product customization affect the range of products made in plants and therefore require plant-level analysis. We measure changes in customization using survey information on whether the plant increased, decreased, or experienced no change in the percentage 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 their catalogs. Thirteen percent 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.

22. The alternative interpretation, in which IT adoption causes a reduction in production times, still requires an explanation of why IT adoption is not more widespread. One possible reason that some plants might not adopt these new technologies, even if they would improve their production times, is that some plants may face greater adjustment costs than others. Here, the IT investments would still generate the reductions in production times implied by the Table III regression coefficients, but the total costs of adopting the IT would make these investments unprofitable for some. "Net returns" (i.e., returns after accounting for both the cost of the new technology and the adjustment costs) would be less for nonadopters than for adopters.

VI.B. IT Adoption and Changes in Production of Customized Products

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

Whether the IT variables are entered separately (column (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 percentage 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 supports the predictions of the theoretical framework in Section III. The adoption of new CNC machines reduces setup time in all specifications in the Table III analysis, consistent with hypothesis H1. 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 for commodity products. Therefore, the adoption of new CNC machines also results in an increase in the production of customized products (hypothesis H2).

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 product design to simple machine instructions, which in turn enables actual fabrication to be done elsewhere. The results in Table IV, 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 "percentage 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

TABLE IV
THE EFFECTS OF IT ON CHANGE IN PRODUCT CUSTOMIZATION, 1997–2002[a]

Dependent variable	(1a) Percent catalog up[b]	(1b) Percent catalog down[b]	(2a) Percent catalog up[b]	(2b) Percent catalog down[b]	(3a) Percent catalog up[b]	(3b) Percent catalog down[b]	(4a) Percent catalog up[b]	(4b) Percent catalog down[b]
Bought new CNC machine	0.842	0.894*					0.946	0.947*
	(0.651)	(0.495)					(0.653)	(0.533)
Adopted 3D-CAD			−0.417	0.804**			−0.479	0.818**
			(0.526)	(0.411)			(0.535)	(0.434)
Adopted flexible manufacturing system					0.427	−2.442**	0.407	−2.566**
					(0.618)	(1.105)	(0.636)	(1.119)
Adopted automated inspection sensors							−1.028	−0.343
							(0.706)	(0.617)
Observations	172		172		172		172	
Pseudo R^2	0.0943		0.0971		0.1159		0.1535	

Data Source. Authors' survey of valve manufacturing plants. See Section IV.

[a] Each pair of columns reports estimated coefficients from one multinomial logit model. Each of the multinomial logit regressions reported in the table includes controls for age of plants (five age dummies), number of shop floor workers, a dummy for unionization, and two dummy variables indicating whether the number of competitors that produce a product that competes with the firm's main product went up or down. Huber-White robust standard errors in parentheses.

[b] The dependent variable has three 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. The means of the percent catalog down, percent catalog up, and no change in percent catalog are .245, .130, and .625 respectively.

*Significant at 10%. **Significant at 5%. ***Significant at 1%.

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 III 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 III results do consistently show that FMS adoption reduces product run times. Depending on overall demand for valve products and the relative demand for catalog versus noncatalog products that FMS adopters face, these plants may increase production after they experience improvements in run times, and this increased production could be concentrated among catalog products.

VII. 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 (hypothesis H3), as well as the relationship between the adoption of new technologies and new HRM (hypothesis H4) practices.

VII.A. IT and Operators' Skill Requirements

The data on the adoption of new IT in this study's intraindustry 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) that are nonproduction or white-collar workers. These studies measure technology by expenditures on computing equipment or estimates of the computer capital stock for the industry.[23] 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

23. 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.

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 the proportion of white-collar workers in an industry or the proportion of nonproduction 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.[24]

Table V 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: mathematics 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, has become less important, or is still equally important. As the means at the bottoms of the columns indicate, a majority of plants report that each of these skills became more important.[25] 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 CNCs—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-solving skills

24. 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.

25. The corresponding values for "decreased in importance" are Mathematics 0.16; Computer 0.02; Programming 0.07; Problem-Solving 0.07; and Engineering Knowledge 0.12.

TABLE V
THE EFFECTS OF IT ADOPTION ON INCREASED IMPORTANCE OF DIFFERENT TYPES OF SKILLS[a]

Dependent variable	(1) Math	(2) Computer	(3) Programming	(4) Problem-solving	(5) Engineering knowledge
Bought new CNC machine	0.127	0.173**	0.271***	0.166**	0.203**
	(0.089)	(0.084)	(0.093)	(0.084)	(0.088)
Adopted 3D-CAD	−0.077	0.107	0.041	−0.105	−0.077
	(0.079)	(0.069)	(0.084)	(0.076)	(0.081)
Adopted flexible manufacturing system	0.273***	0.083	−0.061	0.026	0.038
	(0.083)	(0.080)	(0.106)	(0.095)	(0.102)
Adopted automated inspection sensors	0.007	0.002	0.060	−0.089	0.123
	(0.118)	(0.107)	(0.117)	(0.115)	(0.112)
Pseudo R^2	0.075	0.097	0.137	0.055	0.066
Observations	189	188	184	188	188
Mean	0.57	0.71	0.53	0.68	0.52

Data Source. Authors' survey of valve manufacturing plants. See Section IV.
[a]Dependent variable equals one if skill's importance increased between 1997 and 2002. Probit coefficients evaluated at the mean are shown . Regressions include controls for age of plants (five age dummies), number of shop floor workers, a dummy for unionization, and two dummy variables indicating whether the number of competitors that produce a product that competes with the firm's main product went up or down. Huber-White robust standard errors in parentheses.
*Significant at 10%. **Significant at 5%. ***Significant at 1%.

to program complicated valve devices and then to troubleshoot and reprogram after the first prototype valve device is produced and tested. Consistent with this example (hypothesis H3), the results in Table V 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 total number of shop floor 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.[26]

26. 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 shop floor 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

Furthermore, among those plants that purchased new CNC machines, the number of other "non-CNC" production workers (i.e., total shop floor 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.[27] 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.[28]

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. The IT that is embedded in new CNCs 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, programming, and problem-solving skills among the CNC operators and fewer routine machine skills.

This interpretation of the empirical results—that new IT investments increase the demand for nonroutine problem solving skills but decrease the demand for routine skills—is consistent with the findings of previous case studies and empirical research. For example, Levy and Murnane (2004) report that skill demand increases with increases in computerization due to the

those that 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 percentage of shop floor employees who are CNC operators or in terms of its plant size.

27. 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 that it is because, as our interviews suggest, new CNC machines often replaced multiple older machines.

28. Regression analysis confirms that the 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 shop floor workers, and unionization rates.

give-and-take problem solving that is required with new product design and manufacturing for the case of circuit board design and production. These nonroutine 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 nonroutine cognitive skills. Analyzing data on the U.S. labor market, Autor, Katz, and Kearney (2005, 2006) show that during the past 15 years of rapidly falling computer prices, wages and employment have increased dramatically at 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 the 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 nonroutine problem-solving skills complement the increased computerization of the industry and are not suffering employment losses within plants.

VII.B. IT and HRM Practices

While the role of HRM practices is not incorporated explicitly into our model, a number of studies (Black and Lynch 2001; Bresnahan, Brynjolfsson, and Hitt 2002) find a link between the adoption of new computer technologies and the adoption of new types of work practices. Table VI analyzes the relationship between the adoption of IT and HRM practices in the valve-manufacturing industry during the time period 1997–2002. We study the adoption of three HRM practices: teams, shop floor 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 period 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 VI, we report results from three separate probit models in which the dependent variables measure the adoption of

TABLE VI
THE EFFECTS OF IT ADOPTION ON THE ADOPTION OF NEW HRM PRACTICES, 1997–2002[a]

Dependent variable	(1) Teams	(2) Shop floor meetings	(3) Technical training
Bought new CNC machine	0.305***	0.244*	0.310***
	(0.098)	(0.137)	(0.096)
Adopted 3D-CAD	0.010	0.025	0.172
	(0.101)	(0.108)	(0.112)
Adopted flexible manufacturing system	−0.011	0.016	0.185
	(0.136)	(0.126)	(0.124)
Adopted automated inspection sensors	0.060	0.147	0.259
	(0.171)	(0.127)	(0.175)
Observations[b]	125	88	105
Pseudo R^2	0.185	0.127	0.315
Means	0.42	0.69	0.36

Data Source. Authors' survey of valve manufacturing plants. See Section IV.

[a]Dependent Variable: Equals one if plant adopted the HRM practice between 1997 and 2002. Probit coefficients evaluated at the mean are shown. Regressions include controls for age of plants (five age dummies), number of shop floor workers, a dummy for unionization, and two dummy variables indicating whether the number of competitors that produce a product that competes with the firm's main product went up or down. Huber-White robust standard errors in parentheses.

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

*Significant at 10%. **Significant at 5%. ***Significant at 1%.

these practices. The samples for these three probit models include those observations that did not have the given practice as of 1997, and the dependent variable equals one for those plants that adopted the given practice by 2002.[29] The results in Table VI show a positive and significant correlation between the adoption of IT and HRM, but as in the Table V 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 shop floor meetings. These findings are consistent with the Table V results regarding the impact of computerization on skill demand.

29. The means of the dependent variables in Table VI are the percentages of the plants that had not adopted the practice by 1997 but adopted the practice by 2002. Re-estimating these HRM adoption models on a larger sample that includes those observations that had adopted the given HRM practice before 1997 yields coefficients on the IT adoption variables of similar magnitude and significance.

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 nonroutine problem-solving that is a key part of their job.

VIII. 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 United States 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.

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 set up the production line for new product runs, and also lowering the run time 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—not only changes the quantity of that input and related inputs, but 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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