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

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## I. Introduction

Computer-based information technologies were widely adopted by U.S businesses in the 1990's. Many analysts argue that this widespread adoption of new computer aided information technologies (IT) fundamentally reshaped the U.S. economy by spurring rapid rates of productivity growth, increasing the demand for a more skilled workforce, and by promoting the adoption of new forms of work organization.[1] Several studies conclude that IT investments contributed to macroeconomic gains in productivity (Jorgenson, Ho, and Stiroh, 2003; Oliner and Sichel, 2000), yet most evidence comes from aggregate data that examines the timing of IT investments and the timing of productivity changes for the economy or for broad industry groupings. Firm-level research is less common[2] and analysis here is often based on cross-industry surveys, forcing analysts to examine general measures of IT that may have very different effects in different industrial settings

Missing from the existing empirical literature on the effects of IT on productivity, work organization and worker skills are studies that identify what IT really means in the context of specific production processes with tests of the effects of new IT investments on the efficiency and organization of those production processes.[3] This paper addresses this gap in the literature by conducting an in-depth study of the determinants of productivity in a specific manufacturing production process – valve making. Using personally collected longitudinal data on IT investments, productivity measures, work practices, and worker skills for plants in this industry, we present a series of very straight forward empirical estimates that examine how investments in IT and new HRM practices affect the production process in this industry. While this analysis of rich industry-specific data limits the generalizability of the study, such analysis provides an opportunity to make particularly persuasive empirical tests of the connection between IT and

[1] For research on new HRM practices, see especially Osterman (1994, 2000); and on changes in skills demanded by businesses (Black and Lynch, 2001; Autor, Levy and Murnane, 2003). Levy and Murnane (1992) provide one review of the extensive literature on increasing U.S. wage inequality.

[2] An important exception is Bresnahan, Brynjolfson, and Hitt, (2002) which documents large productivity gains among businesses that adopt new IT along with new methods of work organization.

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

productivity[4] and to gain greater insights into how businesses change to realize productivity gains.

The empirical findings reveal a complex web of changes in businesses that adopt new IT-aided equipment. First, new IT changes how the firm competes. By drastically reducing the time it takes to switch product runs, new IT investments allow valve plants to expand the range of product varieties they produce and moves business strategies away from commodity production in long product runs to customized production in smaller batches. Second, the adoption of new computer-based production technologies also leads to changes in skill requirements of workers. Third, firms that adopt new IT also adopt new human resource practices. Empirical results clearly illustrate that the adoption of new IT machinery entails much more than the installation of new equipment on the factory floor. Underlying these changes is the fact that IT raises productivity by reducing machine setup times, which facilitates the strategic move towards customization.

The next section describes the valve-making production process and provides evidence from an econometric case study of one plant in the industry. Part III presents a theoretical description of the decisions to invest in new IT equipment and the relation of IT to product customization and operating efficiency. Part IV describes the sample of valve making plants that we analyze, and the industry-specific survey we developed, and part V describes trends in these data concerning IT investments, productivity, and the adoption of new work practices in this industry. Part VI presents empirical estimates of the relationship between information technology and productivity at various stages of the valve-making production process. This section also documents the impact of new HRM practices on product-level productivity. In Part VII we use our survey data and the Longitudinal Research Database to document that new information technology has resulted in a move towards the production of more customized products in smaller batch sizes in this industry and the exit of commodity producers from the industry. Part VIII shows that plants that adopt new IT also adopt new HRM practices and increase their demand for technical skills. Part IX concludes.

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

## II. Understanding the Valve-Making Production Process

A detailed investigation of how IT investments affect the productivity, skill demand and work organization of competing businesses requires rich establishment-level data sets. Because existing public data sets on establishments do not measure these detailed characteristics of organizations and their workers, we follow an "insider econometrics" approach in this study – a term we have used to describe a method for developing convincing empirical tests of the effects of organization-specific characteristics on productivity. This approach emphasizes the importance of using insights from field research inside organizations to inform data collection efforts and to construct econometric models. Insider studies also focus on micro-level production units, well below the level of a firm, within a narrowly defined industry setting, so that outputs, inputs and other features of the production process can be measured accurately. Following this approach here, we ground this study in the context of the valve manufacturing industry. This section reports on observations from visits to five plants, including one case study with detailed performance data, which inform how we model and measure valve production in our later econometric tests.

### The Production Process and Information Technologies in Valve Manufacturing

A valve is a metal device attached to pipes to regulate the flow of liquids or gases – such as the flow of natural gas in a heating system, or the control of liquids in a chemical factory. Valves can be a commodity product – as when they control the flow of air in standard air conditioners – or they can be a highly customized product – as when they are built to order for a new chemical plant or a submarine. The production process in valve making is a machining operation.[5] A simple valve is made by taking a steel block or pipe and completing several processes on one or more machines; such as, etching grooves at each end for screwing the valve to pipes; boring holes at different spots to attach control devices; and making and attaching various devices that control the flow.

*IT and Capital Machinery*. Thirty years ago, the reshaping of the steel pipe or block would be done on a work bench by a highly skilled machinist using manual tools. Today, much of valve making is highly automated with new computer-based IT features embedded directly in valve making equipment. The central piece of equipment in the

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

valve making production process is a *computer numerically controlled (CNC) machine* that lines up the block on the pallet of the machine and automatically drills and chips in the proper places based on directions entered into the machine's operating software.[6] CNC machines are now in widespread use in the industry.

As information processing technologies improve, greater computing power is embedded directly into newer CNC machines. Field research revealed numerous examples of increases in machine flexibility and reductions in setup time possible with more technologically advanced CNC machines. The IT element of the CNC machine is in the CNC *controller*. The dramatic decline in the price of computing power in recent years has lead to significant increases in the capability of controllers while simultaneously reducing their cost. The cost reduction for controllers has enabled CNC to add 'axis' capabilities: a 5-axis CNC machine tool can drill holes into a valve at several different angles (or axes) while a 3-axis CNC machine tool would require the valve to be manually repositioned within the machine tool for each new drill angle. Thus, computerization has directly enabled the machine to increase the number of axes on which it can operate, and this has directly reduced the setup-time and increased the flexibility of the machine. There have also been advances in the IT component of CNC controllers that allow the controller to use its computing resources more efficiently. An example is "curve interpolation," which allows CNC machine tools to create smooth curves on a valve instead of having to approximate curves using a large number of linear cuts. This reduces the software program size, which decreases the amount of memory needed to perform a given task, thus lowering setup-time and runtime.

Overall, increases in computing power improved the capabilities of CNC machines considerably. Operators can now program a modern CNC machine more easily through much simpler software interfaces, and each machine can now perform a much wider variety of tasks on the block of steel. Plant managers and engineers demonstrated how investing in technologically more capable CNC machines leads to a reduction in the number of machines needed to produce a given product. For example, in 1980 a typical

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

product at one plant required seven machines; by 2002 that same product would be made on two more advanced CNC machines. The move to a smaller number of more advanced machines to produce a given product has a direct impact on the time in takes to do setup tasks, because there are fewer machines to set up and each is easier to program.

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

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

Another technology that is becoming more common in valve making plants is *three-dimensional computer-aided-design* (3D-CAD). This is a constantly advancing IT method for turning customers' valve specifications into a specific design, and then in some cases, in translating the design to the CNC machines.

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

*Process and Product Improvements*. Many of those interviewed during our plant visits underscored two key operational imperatives for remaining competitive in this industry. First, productivity improvements are important since many plants can make a wide variety of customer orders. There are three elements contributing to the operational efficiency in machining a valve: the *setup-time* of a machine, or the time it takes to program the machine so that it will perform the right combination of tasks to produce the specified valve; the *runtime* of the machine to complete the machining of each unit of valve; and the *inspection time* to verify the quality of the valve. Efficiency gains in these stages are "process improvements." Second, managers also observed that their plants were increasingly relying on a strategy of customizing their production to meet customer needs. Production of commodity valves is increasingly moving abroad to low wage countries. Therefore, many U.S. valve makers are increasing the number of customized products they produce. As manufacturers customize their valves more, the number of units produced in one run, or the batch size of a run, decreases. Increases in product customization with declining batch sizes in a product run reflect "product improvements."

As is obvious from the discussion of new IT advances in valve-making equipment above, the new technologies are critical for achieving process improvements in the different stages of the overall machining process. Reductions in number of machines needed to make a valve directly reduce setup-time and perhaps runtimes as well. FMS technology reduces runtime by coordinating the operations of multiple CNC machines involved in producing a given valve. Automated inspection sensors reduce inspection times. Perhaps less obvious is the critical role that the new IT advances play in the move to product customization. More sophisticated controllers will not only reduce the cost of customizing products, but technologies that reduce setup times will also increase the speed and reduce the cost of making changeovers between product runs.

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

One of the five plants where we conducted interviews and inspections of machining operations worked closely with us to provide their own proprietary data on setup-time, runtime, and machine use for 331 distinct valve products that they made in

2002-2003. These are products they had also made in prior years.[7] Thus, these data provide the opportunity to examine process improvements over time as the plant introduced new machines aimed at lowering setup and production times.

For this plant, the largest component of production times was in setup. Managers indicated their plant was not unusual in this respect. Process improvement gains at this plant would come primarily through reductions in setup times. Reducing the number of machines involved in making a given product by investing in new CNC machines that can perform a wider range of tasks would therefore be an important method for improving operational efficiency. Run times on newer machines would also be shorter, though run times account for a smaller proportion of overall production time.

Purchases of new IT-intensive machinery were not the only source of improving efficiency in the setup stage according to the chief engineer at our case study plant. He gave examples of how changes in work organization and the use of lean production methods also helped the plant achieve reductions in setup-times. In his examples, an off-line problem-solving team was formed to lower setup-time. The team videotaped current setups. After analyzing the video, they brainstormed ideas for reducing setup time, ranked options according to cost-benefit analysis, and then made changes in the setup process. The changes tended to be very straight-forward: organize special tool carts for needed areas (to avoid running elsewhere for tools); re-organize the fixture areas; labeling, painting, cleaning, and organizing. Still, the engineer reported substantial cuts in setup-time – as much as 75% for some products (from 180 minutes to 45 minutes), and modest reductions in runtime.

Using the detailed time series data on 331 products from this plant, we estimate regressions that express setup time and runtime as a function of the number of machines. Results in Table 1 show that reductions in the number of CNC machines used to make a product significantly decrease setup and run times. The log(setup-time) regression shows that a 10 percent reduction in the number of machines reduces setup-time by 9 percent

[7] Some data on these valves extend back from 2003 to 1978, but 75% of the data is for 1999-2003, and all data are only for those valves in production between 1999 and 2003. This data set contains 790 observations for 331 products, or about 2.5 years of data for each product. The data are product-specific data on *scheduled* setup-time and runtime for each machine on which the product will be run. There is no actual production time data, so there is no time-series variation in these data arising from temporal shocks in demand or in production-line failures.

(Table 1, column 1). Equivalently, a decrease in the number of machines from 6 (the mean and median for the data) to 5 reduces setup time by 56 minutes, relative to a median setup-time of 495 minutes. Moreover, the R-squared is large -- for the overall regression it is .60; for the within effects (i.e., by product) it is .42; and for the between effects it is .68. The effects are also sizable for log(runtime). A 10% reduction in the number of machines reduces runtime by 6%. However, because typical runtimes (at 46 minutes) are much shorter than setup-times, and because the typical batch size is very small, the most important quantitative gains are in setup-time reduction. Note that the time series that we have for most valve products is very short, and perhaps as a result, we find no strong time trend reduction in either setup-time (column 2) or runtime (column 5).

The econometric results from this case study reinforce the observations that managers made during our plant visits. Using fewer machines to produce a given product very significantly reduces setup-time. To a lesser extent, it reduces run time. The causal mechanism underlying the results of these simple regressions is quite 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 machines that are easier to program, then setup-times go down. With this smaller number of faster machines, run times also go down.

The estimates from the product-specific regressions above imply that, on average, the reduction of one CNC machine from the machining process reduces setup-time by 56 minutes. However, there are two factors that influence the exact size of the *#machines* coefficient in the setup regression. First, higher-quality CNC machines will reduce setup-time more, so these point estimates on *#machines* reflect the unobserved quality of the CNC machines purchased. Not all products use exactly the same CNC machines. Second, the most complicated products that require especially long setups may benefit the most from purchasing new CNC machines to produce these products. Finally, if the introduction of new machines on products is correlated with the use of "lean manufacturing" processes described above, then some of the gains from using a smaller number of machines will reflect the simultaneous returns to lean manufacturing. However, the overall conclusion is very clear. For a typical product at this company, a switch from an average set of older CNC machines to an average set of newer CNC machines will reduce setup time by about an hour. This is a technological relationship – better CNC machines improve productivity. Most important, these results are not subject to selection bias: if any random new manufacturer introduces new machines with these capabilities for products like these, their setup-time reductions should match these.[8]

**III. The Strategic Investment in IT and HR Practices**

Valve manufacturing is a batch process. Products in many other manufacturing industries are also made in batches. Each compound in chemical production, each book in publishing, and each new piece of furniture in high volume furniture production is a new batch. The same equipment is used to manufacture the different product types, but the new product specifications require reconfiguring the specific operations of the machines. In all of these settings, just as in the econometric case study of the valve maker above, the setup-time when machines are reconfigured from the requirements of one product run to the next is often a large part of overall production time.

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

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[8] Note that we also obtained data from this company on the time between order and shipment of their products, by product. It is noteworthy that we find no time series reduction in the value of shipment time, even when we estimate product fixed effects. While the company president had not conducted any such empirical analysis, he noted there were no changes over time in shipment time. Even though setup time and runtime have fallen as they have shifted their product mix towards more customized products, these time savings have been offset by increases in the time communicating with customers. Thus, mean shipment time is unchanged over time.

costs of commodity products made in long batch runs, and more in terms of making customized products designed for specific customers that earn higher prices – and this change takes place in part because IT lowers the cost of switches between products.[9]

To clarify the tradeoffs that firms face with improvements 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 – commodities (co) that have long batch runs, but lower product market prices ($P_{co}$); and customized products (cu) that have short batch runs, but have higher product prices ($P_{cu}$):

$$(1)\quad \pi = N_{co}B_{co}P_{co} + N_{cu}B_{cu}P_{cu} - [(w+r)(S_{co} + R_{co}B_{co} + I_{co}B_{co})N_{co}]$$
$$- [(w+r)(S_{cu} + R_{cu}B_{cu} + I_{cu}B_{cu})N_{cu}] - M_{co}B_{co}N_{co} - M_{cu}B_{cu}N_{cu} - D(N_{cu}) - P_{IT}IT$$

where $\pi \equiv$ profits

subscripts *co* $\equiv$ commodity, cu $\equiv$ customized product
$S_j \equiv$ hours to setup machine to run product; $j = co, cu$
$R_j \equiv$ hours to run each piece of product; $j = co, cu$
$I_j \equiv$ hours to inspect each piece of product; $j = co, cu$
$B_j \equiv$ average batch size (number produced per scheduled batch) $j = co, cu$
$N_j \equiv$ number of batches of product $j$; $j = co, cu$
$D \equiv$ design and advertising costs (as a function of $N_{cu}$, the number of batches of the custom product)
$M_j \equiv$ materials costs per unit; $j = co, cu$
$P_j \equiv$ average price of product $j$, $j = co, cu$
$w \equiv$ wage rate
$r \equiv$ maintenance cost of capital
$P_{IT} \equiv$ price index of new IT capital
IT $\equiv$ dollar value of new IT capital

Equation (1) simply emphasizes that 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 ongoing costs of IT. The time costs of production are the wage and the

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

rental cost of capital for the time that it takes to run the product. Thus, productivity is increased if production time falls. Finally, for customized products, we assume that there is a design and advertising cost, $D(N_{cu})$.

Operator labor hours per batch equal:

(2) $L_j = ( l_1 S_j + l_2 R_j B_j + l_3 I_j B_j )$ ; for $j = co, cu$

where $l_1 = l_2 = l_3 = 1$ if one person runs each machine, which is typically true. Our plant visits indicated that setup time is the most important controllable component of production time. Next, assume that all three components of production time are a function of IT-imbedded capital and other variables. While labor hours in (2) are a fixed percentage of production time, we also assume that a more skilled worker or highly trained operator can do a setup in less time:

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

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

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

where $IT_j^{Set}$, $IT_j^R$, $IT_j^I$ are the IT-imbedded machinery that are used in the setup, running, and inspection of the product, and $X$ is a vector of control variables. The functions in (3)-(5) may well be non-linear, if, for example, setup time is assumed to be more responsive to improvements in information technologies for those products that have higher setup times (i.e. custom products).

With this model of the manufacturing process, how does a fall in the price of a unit of IT affect the firm? Without any loss in generality, we simplify with several assumptions that help highlight the key results.[10] We assume that the predominant effect

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[10] In their model, Milgrom and Roberts (1990) make 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 and/or non-linear adjustment costs for changing the plant size or for finding new customers. For the valve industry, we envision both of these constraints. That is, firms are price takers for small increases in their output, but as output rises too much, the market is saturated and prices fall. Similarly, we are modeling the short run decision to become more customized, and in the short run, the costs of significantly increasing the size of the plant or seeking large numbers of new customers are accelerating, and therefore limit the increase in the

of IT on production time is its impact on the setup-time component (thus dropping runtime and inspection time for convenience); we assume that the effect of IT on the setup-time of commodities is zero (essentially assuming that IT reduces the setup-time of commodities less than that of customized products). Then, profits will be affected by a fall in the price of IT in the following way:[11]

$$\begin{aligned}(6)\quad \frac{\partial \pi}{\partial P_{IT}} &= [B_{cu}P_{cu} - (w+r)S_{cu} - M_{cu}B_{cu} - D][(\frac{\partial N_{cu}}{\partial S_{cu}})(\frac{\partial S_{cu}}{\partial IT})(\frac{\partial IT}{\partial P_{IT}}) \\ &- [(w+r)N_{cu}](\frac{\partial S_{cu}}{\partial IT})(\frac{\partial IT}{\partial P_{IT}}) - P_{IT}\frac{\partial IT}{\partial P_{IT}} - IT\end{aligned}$$

1. The first term is the increase in profits due to an increase in the number of custom batches, $N_{cu}$, that the plant produces (given positive net revenues from custom product production). The number of customized batches is likely to rise because setup-time falls when IT is increased.

2. The second term is the increase in profits resulting from a decrease in setup-time due to increased IT, holding constant the product mix (or $N_{cu}$).

3. The third term is the decrease in profits from purchasing more IT.

4. The fourth term is the increase in profits from a lower price of IT.

Based on this model, we posit several hypotheses:

H1. There will be an increase in the adoption of IT-imbedded machinery, which in the valve making industry includes equipment like new CNC machines, new 3D-CAD/CAM design equipment, FMS, and computerized inspection equipment.

In a period like the one we are studying with dramatic declines in the cost of computing and equally dramatic increases in the capability of computer-aided manufacturing equipment, and with relatively long time horizons to recoup on the marketing costs, a decrease in the price of IT will lead to widespread adoption of low cost computer aided production equipment.

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optimal amount of customized product that is produced. Thus, our model of changes in product mix and IT purchase should be considered a model of short-run marginal changes.

[11] We assume that there is fixed batch size for each product class, commodities and custom products.

H2. IT improves production efficiencies.

This hypothesis is built into the model as the assumptions that underlie equations (3)-(5). We base these assumptions on the evidence from plant visits. Setup-time, runtime and inspection time should fall when IT machinery relevant to these processes is adopted. Moreover, it is likely that setup-time time will fall more for customized products since IT is aimed at improving setup flexibility.

H3: IT promotes more product customization by producers.

As long as IT causes a larger decrease in the setup-time for custom products than it does for commodities**,** or setup-time is a larger percentage of production time for custom products than for commodities, then adoption of IT equipment associated with lower setup costs will move production towards some combination of more customized production and smaller batch production. The prediction also assumes that net revenues for the plant's production of the customized product are positive.

H4. Given rising short run profits from product customization, plants that survive in the industry over time should be those that produce customized products (or that move towards product customization), and those plants that enter the industry should produce more customized products.

Finally, we posit a fifth hypothesis that is not considered directly in the model.

H5: IT adoption may require new HRM practices and new worker skills.

While the role of HRM practices is not considered in the model, a number of studies (Milgrom and Roberts, 1990; Bresnahan, Brynolfsson and Hitt, 2002) argue that the adoption of highly automated and technically complex manufacturing equipment may require the adoption of new types of work practices and require new sets of skills from workers. The data collected for this study permit us to examine these further hypotheses that suggest that adoption of new technologies will coincide with changes in HRM practices and in the kinds of skills workers need to operate new technologies.

**IV. The Valve-Making Industry Survey and the LRD Survey**

The plant visits and interviews with experienced industry practitioners help identify concrete examples of new IT-based equipment, and identify what parts of the overall machining process these IT advances would impact. To examine the impacts of IT investments on performance more broadly throughout the entire industry, we developed a customized survey for valve plants. This survey measures process improvements in each of the three production stages, product improvements and increasing customization of valves, and investments in new IT-enhanced production machinery. The survey is also designed to look at a broader set of possible changes associated with new IT investments and also asks for information on worker skills and HRM practices.

*The Sample of Valve Industry Plants*. Using the insights from our field research, we designed, pre-tested, and conducted a customized industry survey in 2002.[12] 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 universe of 416 valve making plants, 212 plants, or 51%, provided responses to the survey questions described in this section via telephone interviews.[13] Empirical results in the study are based on the responses from these 212 valve-making plants.

*Process Improvement Measures*. Efficiency gains in machining processes are *product-specific* measures. We asked each respondent to look up data for "the product

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

[13] 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.

you have produced the most over the last five years" for the following key indicators of process efficiency:

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

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

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

*Product Improvement Measures.* Because product improvements involve changes in the number of products a plant makes, these measures are *plant-specific* measures. To measure whether plants had increased customization of their products, the survey asks the following questions:

*Batch Size: What was the typical batch or lot size of the products that you produced in 2002 (1997)?*

*Percent Catalog: What percent of your customer orders are directly from your catalog with no design change?* Responses to this question are only available for 2002.[14]

*Information Technology Advances in Equipment*. To measure investment in new IT equipment, the survey asks the following questions:

*Number of Machines: In order to produce one unit of this product today (and in 1997) how many machines do (did) you employ?*

*New CNC Machines: How many CNC machines does the plant have and how many are less than 5 years old (newcnc), 5 to 10 years old, and more than 10 years old?*

*Flexible Manufacturing Systems (FMS): Does the plant have FMS technology (where two or more 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/CAM design equipment: Does the plant use three-dimensional CAD software for designing new products and in what year was this software first used?*

[14] We asked for 1997 values as well, but few respondents could answer the question for 1997 with a response rate of 33%.

The first IT question above concerning "number of machines" is a *product-specific* question, and pertains to the plant's main valve product over the last five years. The other IT questions are *plant-specific* questions. Other plant-level survey questions concerning human resource management practices, skill demand, and competitive market conditions are described below with the empirical results.

*LRD Data Match*

In the analysis below, we complement data from our valve industry survey with data on valve making plants from the Census Bureau's Longitudinal Research Database (LRD) the longitudinally connects the Census of Manufacturing data. To date, only data through 1997 are available from the Census of Manufacturers (conducted every five years), so we examine data for the 1997 cross-section of plants, and conduct longitudinal analyses using the LRD spanning the 1992-1997 period. The sample size for the matched dataset is 178.

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

Hypothesis H1 makes the straightforward prediction that, with dramatic declines in the cost of computing, plants will increasingly adopt new IT-enhanced production equipment. This section reports trends in the adoption of new production machinery in the valve making industry, as well as trends in productivity measures and in HRM practices.

Trends in Adoption of IT-Enhanced Production Machinery

Panel A in Table 2 examines the time path of adoption for three types of IT equipment for which the survey asks the year of adoption. All three show large increases in usage since 1980. The highest rates of adoption for the plant's first CNC machines occurred during the 1980's, but throughout the 1990s, plants invested heavily in new CNC machines--74 percent of plants purchased new CNC machines from 1997-2002. These new machines, described in section II above, are heavily IT driven. Investments in other new computer-based technologies – in 3D-CAD/CAM and automated sensors – show the largest growth after 1995. Our survey also asks about the use of an additional set of computer-aided technologies between 1997 and 2002 (the years for which we measure manufacturing times). Trends in the use of new technologies over this five-year period are reported in Table 3. As discussed in section II, bringing new more advanced CNC machines on line results in a reduction of the number of CNC machines it takes to produce a product. Line 5 in Panel A reveals that, on average, it took 19 percent fewer machines to produce a given valve product in 2002 compared to 1997. According to the figures in lines 1-3 of Panel C, FMS technology, automated inspection sensors, and 3D-CAD/CAM technology were newly adopted by an additional 15%, 14%, and 39% of our sample of valve making establishments between 1997 and 2002. The conclusions from Tables 2 and 3 are clear: *during the 1990s, plants in the valve-making industry invested heavily in computer-based new technologies.*

Trends in Measures of Operating Efficiency and Product Customization

Table 3 also reports trends in process and product improvements in these valve-making plants over the period from 1997 to 2002. Lines 1-3 reveal that, on average, plants realized large declines in production times for making their most common product in each of the three production stages. The largest decline is in the setup stage. The survey also reports changes in customization over this period as measured by the survey questions on batch size (Panel B). The 1997-2002 period is marked not only by improvements in process efficiency but also greater customization as batch sizes also decline. These batch size reductions are widespread in the industry with fully 58 percent of the sample reporting smaller batch sizes in 2002 than in 1997.

Trends in the Adoption of New HRM Practices

The survey asks about the adoption of new HRM practices. Panel B of Table 2 reports the time path of adoption for certain HRM practices for which the survey asks the year of adoption. The use of teams, training programs and bonus/incentive pay plans all increased since 1980 with the highest rates of adoption of these practices occurring after 1990. Table 3 reports trends for a somewhat broader set of HRM practices between 1997 and 2002 (Panel C, lines 6-10). Valve plants increasingly adopted new training programs and more team-based methods of job design, and more meetings with operators. Direct incentive pay plans, excluding bonus payments, are less common than the other HRM practices.[15] Basic training programs in reading and math, technical skills training, and teams were adopted by 12%, 21%, and 30%, respectively, between 1997 and 2002.

The patterns in Tables 2 and 3 show that the trends in IT investments, productivity measures, and new HRM practices mirror trends observed in the broader U.S. economy. The 1990's in the valve industry is a decade marked by rapid adoption of new machinery that incorporates many IT-based technological improvements, significant improvements in productivity of operations, increases in product customization, and a growing reliance on new methods of work organization.

While these trends demonstrate that product and process improvements are happening at the same time that the industry is investing in new IT-enhanced machinery and new HRM practices, the empirical work to follow examines whether the improvements in various aspects of machining times or declines in batch size over this period are concentrated in those plants that have made investments in these new technologies and work practices. Also, though not reported in Tables 2 and 3, it is not the case that some plants adopted all of the technologies and practices while others adopted none. Because different plants adopted different pieces and combinations of IT equipment, the models will also be able to make a particularly discriminating test of the effects of the IT measures on productivity. Specifically, the econometric models examine whether specific pieces of equipment that impact individual stages of production (e.g., automated inspection equipment and the inspection stage) affect the specific stage of production in which it is located.

## VI. Estimates of the Determinants of Productivity at the Product Level

Table 3 documents significant process improvements in valve-making plants between 1997 and 2002. This section focuses on the determinants of those improvements. 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

[15] Interviews suggested that direct incentive pay is difficult to adopt in an industry that makes customized products. The increase in the use of incentive pay is smaller than the increase in other HRM practices in the valve industry. By 2002, incentive pay is used by 31% of plants and special bonuses by 36% of plants, so about 50% of plants have one or the other (see Table 2), but interviews suggest that these incentives are a very small percent of total pay and are used rather erratically. As a result, we do not focus on the incentive pay plans in our HR analysis below.

technologies and new HRM practices to see if process improvements occur in those plants that adopt new technologies or work practices.

(7) $\Delta\ln(\text{ProductionTime}) = a + \mathbf{b_1\Delta\ (NewTechnology)} + \mathbf{b_2\Delta\ (NewHRM) + b_3X} + e_1$

The dependent variable in (7) is the log change in Production Time between 1997 and 2002 – where Production Time refers to setup-time, run time and inspection time (as in equations (3)-(5) above). The vector **Δ(NewTechnology)** measures the adoption of new technologies expected to reduce these machining times – the adoption of FMS, automated inspection sensors, and 3D-CAD/CAM technologies, as well as the change in the number of CNC machines needed to produce the plant's main product. The vector **Δ(NewHRM)** measures the adoption of new HRM practices, such as work teams and training programs since 1997, and **X** is a vector of controls including the age of the plant, union status, and plant size measured as number of workers to test whether the change in machining efficiency is affected by these additional factors.

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

Hypothesis H2 states that IT equipment will improve operating efficiencies of the various stages. Consistent with this hypothesis, the results in Table 4 demonstrate that investments in new IT-machinery have improved process efficiency by reducing all components of production times. The results are remarkably straightforward and striking: the adoption of new technologies into a given stage of the machining process reduces production times in that stage significantly. Using fewer machines reduces setup-times (column 1). Run time also declines with the use of fewer machines, but less significantly. Both of these results for this industry-wide sample of valve plants mirror the results from the econometric single-plant case study reported in Section II. Runtime declines significantly in plants that adopt FMS technology (column 2). Inspection time declines with the introduction of new automated inspection sensors (column 3).[16] The basic pattern of results in Table 4 can be summarized simply. *New IT-based production machinery improves the efficiency of the stage of production in which it is involved. New*

[16]We find no significant effects of IT on shipment time, consistent with the findings from our econometric case study.

*computer technologies do not improve the efficiency of phases of machining in which they are not involved.*

The theoretical discussion of section III draws special attention to reductions in setup times. There, we argued that reductions in setup time due to new IT investments make product changeovers faster and cheaper, resulting in a move toward greater customization. These savings in setup times from the adoption of more advanced CNC machines shown in column 1 of Table 4 are important. According to the means on production times reported in Table 3, setup times in 1997 were the largest component of overall production time, accounting for almost one-half of overall production time. We can use the coefficient in column 1 of Table 4 to calculate the impact of IT investments on setup time. Among plants that did experience a decrease in machines after 1997, the mean change in ln(machine) is -.65 and, using the coefficient in column 1 of Table 4, this implies a reduction in setup time of .434 ln-units, which is 59% of the actual reduction in setup time for these plants. This IT investment therefore accounts for a large part of the overall reduction in setup times between 1997 and 2002 reported in Table 3.

<u>Estimates of the Effects of HRM Practices on Machining Times</u>

According to our theoretical framework, production time (and, in particular, setup time) is likely to be shorter if the plant has more skilled operators. Table 5 replicates the regressions in Table 4 but adds variables measuring the adoption of certain HRM practices (technical training, basic training and teams) between 1997 and 2002. According to the results in Table 5, plants that introduce technical training programs also realize an additional reduction in setup and run times.

These efficiency regressions find no apparent effects of other HR practices such as teams or basic training. However, it is important to remember that we are modeling the efficiency gains over time for one specific product, not the overall efficiency of the plant. Teams may be less likely to have a direct effect on product efficiency as compared to overall plant efficiency. The results in Table 5 demonstrate that *initiatives designed to improve the specific skills needed to operate new technologies in the plant are in fact the initiatives that improve the speed of machining operations during a product run.*

Assessing Potential Biases in Estimated Productivity Effects of IT and HRM

Tables 4 and 5 report results from simple first-difference models of the determinants of changes in production times between 1997 and 2002. Using very detailed industry-specific measures of IT-enhanced production equipment and plant-specific HRM practices, we find that new IT equipment improves the operational efficiency of the production stages in which it operates, while new technical training programs have their own independent effect on setup and run times. Since these pieces of equipment and HRM practices are not universally adopted, the question naturally arises as to whether the estimated improvements in manufacturing times or product customization would actually be enjoyed by those plants that have yet to adopt the new technologies. That is, is the reason behind the non-adoption of new IT and new HRM practices in some plants the fact the non-adopters would not experience the same improvements in efficiency?

First, considering the possibility of simultaneity bias, the rich detailed data that allow us to study improvements in the efficiency of specific machines – or the introduction of the new CNC's, FMS, and automated inspection sensors – limit the likelihood of simultaneity bias. Consider, for example, the setup-time regression. Based on plant visits and our understanding of the production function, there is no reason for a decline in setup-time to cause a decline in the number of machines in use. The only way that setup-time can be reduced over time for the same product is if there is new technology or if workers are better able to use the existing technology. Moreover, our data do not include short term shocks to production such as machine failures that could be correlated with changes in input use including our IT measures. The efficiency measures are typical times, not today's times. Thus, simultaneity problems are avoided with these data.

Second, consider the possibility of omitted variable bias. The pattern of results in the regressions provides evidence about the likelihood of this bias. In the setup time regression, new machines improve efficiency; in the runtime regression, FMS improves efficiency; in the inspection regression, automated sensors improve efficiency. In each regression, the IT investment that is most likely to improve efficiency does, and the others that should have no effect in that regression have no effect. Thus, it is very clear that there is no one omitted variable that is simply correlated with all IT investments and that improves all measures of efficiency. A plant-wide omitted variable (such as better skill of plant management) does not vary across the three different stages in a production run within a given plant, and therefore cannot account for the pattern of results in Tables 4 and 5. One would need to identify a series of omitted variables with different correlations with the IT investments to produce omitted variable biases for each stage of production.

Third, consider the possibility of selectivity bias at the product level or at the plant level. The coefficient estimates for the IT variables in the efficiency regressions reflect the specific mix of products and machines that are found in the particular plants purchasing new IT-enhanced equipment. In our data, we do not have measures of the quality of the new CNC machines that are introduced from 1997-2002 in these plants. So these regressions simply show that, given the typical quality of CNC machine purchased by valve-makers in 1997-2002, the average setup-time falls due to the new CNC (because it lowers the number of machines used per product setup). Similarly, we do not control for how sophisticated these valves are – we simply look at setup, run, and inspection times for the main product in each plant. Thus, the coefficient estimates in Tables 4 and 5 are average expected efficiency gains for the typical valve-maker when a typical new CNC was introduced in 1997-2002. Therefore, if the CNC adopters in our sample period purchased higher-quality CNC's than will the plants purchasing CNC's after 2002 (which we suspect is unlikely), or if the adopters in our sample produce more sophisticated products than post-2002 adopters, then the future adopters of the new CNC would see smaller reductions in production times from CNC's. At a minimum, what these regressions do show is that if a plant is randomly given new CNC machinery of average quality for these adopters, and if this plant has a product mix that is typical for the industry, that plant will experience sizable efficiency gains from the new IT.

In fact, there are also important reasons why the regression estimates in Tables 4 and 5 are likely to underestimate the efficiency gains from IT. These production time regressions refer to the 'product produced the most' in these plants, but new IT is especially valuable because it allows plants to design and build new valves that are more complicated than the ones that were produced in the past or ones that are produced the most. The gains to IT should be bigger for new more customized products than they are for older standardized products or for the plant's current most common product.

## VII. The Gains to IT and Customization in the Valve-Making Industry

Two hypotheses in the section III model – increases in adoption of IT (H1) and reductions in production times due to new IT (H2) – are supported by the analysis in sections 5 and 6. The theoretical framework presented in Part III also suggests that these changes resulting from falling prices of IT should also lead to increases in profits given reasonable estimates for values of the parameters in equation (6). We cannot test this hypothesis because profit data are not available. Our sample consists largely of privately held small firms that would not report profit figures. Matched data from the LRD survey also does not provide profit information. An alternative plant-level performance variable which is available in the LRD is value added. Since the productivity literature often estimates value-added models, we also estimate standard models of the effects of capital, labor, and worker skills on value added using the LRD data on these plants, and compare these results to results obtained from value added productivity models that are augmented with data from our own survey of these plants. We report and discuss these results in greater detail in the Appendix. The results from these value-added models are not particularly illuminating as one might predict from the section III model. The impact of IT on value-added is likely to be ambiguous because a decline in the price of IT and a move to more customized products implies several changes that impact value added measures in offsetting ways. Customized products should sell at higher prices than commodities which would increase value added, but quantities produced could go down thereby reducing value added.

With profit data unavailable and with ambiguous predictions about the effects of falling IT prices on value added, we turn to tests of the remaining hypotheses presented in section III. This section assesses two plant-level hypotheses that we derive from the model: customization should rise when plants invest more in new information technologies (H3), and plants adopting a customization strategy should have lower exit rates and higher entry rates in the industry over time (H4).

Our survey provides two measures of plant-level customization, but time-series data on only one of the measures. First, low values for the question about 'typical batch size' (BATCH) are assumed to reflect a strategy of customization, because more customized products have small batch sizes. However, commodity producers can also produce in small batches if their machinery is highly flexible due to new IT. That is, a plant might produce only two valve products all year, $V_1$ and $V_2$, but if the machinery is highly flexible, they will produce a small batch of $V_1$ as soon as an order comes in, then switch to a small batch of $V_2$ as soon as an order for it comes in, and so on. Therefore, we have a second measure of customization in our survey, the percent of the firm's output that is ordered from their catalog (PCTCAT). High values for this variable imply the production of more commodity products, since products with detailed features designed to specific needs of individual customers would not be products in a catalog. We create a dummy variable for low catalog use (CUSTOMIZED) which equals one when less than 90 percent of the product is ordered from the catalog: 60% of our plants are CUSTOMIZED. In our data set of 212 plants, the correlation between BATCH and PCTCAT is a significant .15 and the correlation between BATCH and CUSTOMIZED is also significant at -.32. The means tell the story clearly:

| | Plant Has CUSTOMIZED Production | |
|---|---|---|
| | Yes | No |
| BATCH size | | |
| Mean | 728 | 6259 |
| Median | 30 | 675 |

Plants that design products to customer specifications have much lower batch sizes. Because our only time series information is on batch size, we use BATCH as our measure of customization. While it is possible that the BATCH variable could reflect production-line flexibility and constant switches of production runs among small numbers of commodity products, BATCH also captures differences in customization as reflected in correlations with catalog variables.

We include two measures of new IT investments in the change in batch size regressions: (1) the percentage change between 1997 and 2002 in CNC machines used to produce a unit of the key product; and (2) a dummy variable (New High IT) that equals one if the plant introduced at least two of the following three types of equipment between 1997 and 2002—a new CNC machine, flexible manufacturing systems, or automated inspection sensors.[17]

As displayed in Table 6, customization rises (batch size falls) when plants introduce new IT technologies. In column (1), the dependent variable is the percentage change in batch size between 1997 and 2002. The column (1) results show that batch size falls when the number of CNC machines used on a given valve product falls. In columns (2) – (4), the dependent variable equals one if the plant adopted a customization strategy by lowering its batch size from 1997 to 2002. The regression results show that batch size falls when plants introduce High New IT or when they lower the number of CNC machines used for a given valve product.

In sum, when plants introduce new IT-enhanced production machinery, batch sizes go down. A smaller number of more powerful CNC machines or the introduction of some combination of new CNC machines, flexible manufacturing systems, or automated inspection sensors allows the plant to produce smaller batches as a way of meeting more specific needs of customers for their main product or as a reflection of the overall increase in specialty production across all valve production of entire plant.

Hypothesis H4 also concerns increases in customization in the industry. It states that a strategy of greater customization should increase the firm's probability of surviving in the valve industry. Testing this hypothesis requires measures of customization for all plants in the industry over time so that we can track customization of plants that enter and exit the valve industry. Economists have not previously measured customization *per se*, but have focused instead on "specialization." Industrial organization studies have focused on trends in specialization within an industry by studying the Primary Product Specialization Ratio (PPSR). The PPSR is the fraction of plant output accounted for by the plant's primary seven-digit SIC product. Increases in the PPSR therefore demonstrate that plants in the industry are specializing in specific 7-digit products.

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[17] The variable New High IT captures the idea suggested by the Milgrom and Roberts (1990) model that falling prices of IT should result in plants changing multiple complementary practices at the same time. If the technologies at the plant interact, the technologies are likely to be complementary.

Since the PPSR measure is available for every plant in the LRD valve industry data (N=1529 plants for 1992), we use it as a way of measuring customization in the industry. For the smaller sample of plants that responded to our own industry survey, we match their PPSR measures from the LRD data set to our survey data. In this matched data set, the correlation between BATCH and the PPSR is -0.21 and is significant at the 5% level.[18] That is, plants that are more specialized by producing output in a small range of 7-digit valve products are the same plants that produce in smaller batches.[19] Specialization is positively correlated with customization.

Table 7 shows new entrants to the valve industry are more likely to be specialized (high PPSR) producers, and thus apparently more likely to be customized producers. These results are unchanged if we control for differences in plant size, or in value added and capital intensity (columns 1 through 3).

Table 7 also shows that the probability that a firm will exit the valve industry falls with specialization. Specialization increases the survival probability of a plant. That is, plants that existed in 1992 but were no longer in operation in 1997 were less likely to be specialists. However, this result only holds for plants larger than 50 workers, and is strongest for plants larger than 100 employees (columns 4 through 6). PPSR has no effect on plant closing probabilities among the smallest valve plants.

Thus, according to these patterns of entry and exit in the LRD Census of Manufacturers, the U.S. valve-making industry, like other U.S. manufacturing industries, has been shifting towards plants that are specializing in a narrower range of 7-digit product classes. Given the correlations between the PPSR specialization measure and the BATCH customization measure in our own survey, the valve plants that specialize are also more likely to produce more customized products using greater levels of new information technologies.

## VIII. The Relationships Between IT, HRM and Skill Demand

While the role of HRM practices is not incorporated in our model, a number of studies argue that the adoption of highly automated and technically complex

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[18] There are 178 plants in our matched dataset but only 110 of these plants reported batch size data for 1997.

[19] The opposite could be true. The PPSR measure would be positively correlated with batch size if commodity producers focus on making only one 7-digit product. The data indicate this is not the case.

manufacturing equipment may require the adoption of new types of work practices and require new sets of skills from workers. Table 8 analyzes the relationship between the adoption of IT and HRM practices during the 1997-2002 time period. We study the adoption of three HRM practices: Training (technical or basic), Teams, and Information Sharing (formal meetings). In columns (1) and (2), the dependent variable equals one for "New HRM Index" – if the plant introduced at least one of these three HRM practices; and in columns (3) and (4), the dependent variable equals one for "High New HRM Index" if the plant introduced at least two of the three practices. We include two comparable measures of IT adoption in these models: "New IT Index" equals one if the plant introduced at least one of the following: New CNC machine, flexible manufacturing systems (FMS), or automated inspection sensors; and "High New IT Index" equals one if the plant introduced at least two of these forms of IT.

The results in Table 8 show a positive and significant correlation between the adoption of IT and HRM. A plant that introduced at least one form of new IT between 1997 and 2002 was significantly more likely to introduce at least one new HRM practice during this time period. And, High IT adopters are also more likely to be High HRM adopters.

We next consider whether the introduction of IT is significantly correlated with an increase in the demand for certain types of worker skills. In Table 9, we present regressions in which the dependent variable equals one if the plant reported that a particular skill's importance increased between 1997 and 2002. We collected data on six types of skills: math skills, computer skills, skills for programming machine operations, problem-solving skills, cutting tool knowledge, and skills in running multiple machines. The same two measures of IT adoption are used in this table as in Table 8 – New IT Index and High New IT Index. The first set of regression results (row 1 of Table 9) show that New IT is positively correlated with increases in the demand for computer skills, programming skills and cutting tool knowledge (at the 1% level). In addition, the correlation between IT and the demand for problem-solving skills is significant at the 10 percent level.[20] When the High New IT variable is added to these regressions (row 2), it

[20] Interviews during plant visits indicated that the use of teamwork (and not IT investments themselves) made problem-solving skills more important. Consistent with this claim, an increase in the importance of

is clear that plants with High New IT are plants that experience an especially large increase in the demand for computer skills among operators.

## IX. Conclusion

Our central proposition is that the investment in new information technologies in the 1990s changed the competitive strategy of manufacturing firms—firms in the U.S. increasingly shifted to the production of customized products. 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 has been lacking to test the proposition. Most empirical researchers investigating the returns to IT investments have focused on the productivity gains, though well aware that they are likely to be underestimating the total returns to IT investments. 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 mix.

Using personally collected longitudinal data on specific IT investments, productivity measures, work practices, and worker skills for plants in the valve-making industry, the results 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 technologies that are heavily computerized clearly raise productivity by lowering the time it takes to setup the production line for new product runs, and also lowering the runtime and the inspection time during production. We also document that IT adopters increase the customization of their products, and the efficiency gains due to new IT investments help explain this change in business strategy – lower setup time increase the efficiency and lower the cost of customized production in short batch production runs. In addition, plants that adopt new IT technologies experience an even broader set of organizational changes since these plants are also more likely to adopt new work practices and require higher levels of skills

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problem-solving skills is correlated with the introduction of teams (correlation = 0.14, significant at 5% level), but teams were also fairly widespread prior to 1997 (35% had teams).

from their operators. Thus, the falling price of an input – the price of computerized capital -- changes not only the quantity of that input and related inputs, but it also changes a business's competitive strategy as well as the work practices and skill requirements of the workforce 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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**Table 1**
**Econometric Case Study: The Effects of IT on Process Innovation within One Plant**

| Dependent Variable | Means (s.d.) | Log (Setuptime) | Log (Setuptime) | Setuptime | Log (Runtime) | Log (Runtime) | Runtime |
|---|---|---|---|---|---|---|---|
| **Log (# machines)** | 1.72 | 0.876*** | 0.903*** | | 0.602*** | 0.632*** | |
| | (0.48) | (0.048) | (0.051) | | (0.046) | (0.048) | |
| **# machines** | 6.07 | | | 55.69*** | | | 8.70*** |
| | (2.87) | | | (3.24) | | | (2.47) |
| **Year** | 1998 | | 0.005 | | | 0.003 | |
| | (6) | | (0.003) | | | (0.003) | |
| **$R^2$ - within** | | 0.42 | 0.43 | 0.39 | 0.27 | 0.29 | 0.03 |
| **between** | | 0.68 | 0.68 | 0.49 | 0.57 | 0.56 | 0.21 |
| **overall** | | 0.60 | 0.61 | 0.44 | 0.48 | 0.49 | 0.17 |
| **N** | | 790 | 762 | 790 | 790 | 762 | 790 |
| **Mean** | | 6.15 | | 623.2 | 3.93 | | 750.6 |
| **(s.d.)** | | (0.81) | | (507.9) | (1.43) | | (325.7) |
| **Median** | | 6.20 | | 495 | 3.82 | | 46 |

Note: Fixed effects regression for product; standard errors in parentheses.
*** Significant at the 1% level.     Number of products=331

**Table 2**

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

| Panel A: Percent of Plants with Computer-Aided Production Technologies | | | |
|---|---|---|---|
| Year | First CNC Machine | Automated Inspection Sensors | 3-D CAD/CAM Design |
| 1980 | .25 | .01 | .01 |
| 1985 | .48 | .03 | .02 |
| 1990 | .66 | .10 | .09 |
| 1995 | .78 | .13 | .24 |
| 2000 | .86 | .25 | .63 |
| 2002 | .87 | .28 | .73 |

| Panel B: Percent of Plants with New HRM Practices | | | |
|---|---|---|---|
| Year | Teams | Training (basic or technical) | Incentive Pay or Special Bonus |
| 1980 | .03 | .17 | .10 |
| 1985 | .06 | .21 | .16 |
| 1990 | .14 | .29 | .21 |
| 1995 | .34 | .50 | .26 |
| 2000 | .58 | .72 | .45 |
| 2002 | .63 | .75 | .50 |

**Table 3**

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

| *Panel A: Product-Level Variables* | *Median Value 1997*[1] | *Median Value 2002*[2] | *Mean Value 1997*[1] | *Mean Value 2002*[2] | *Log change between 1997 and 2002* |
|---|---|---|---|---|---|
| *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 |
| *Number of machines* | 6 | 5 | 5.63 | 4.97 | -0.189 |

| *Panel B: Plant-Level Variables* | *Median Value 1997* | *Median Value 2002* | *Mean Value 1997* | *Mean Value 2002* | *Log change between 1997 and 2002* |
|---|---|---|---|---|---|
| *Batch Size* | 150 | 68 | 3152 | 2870 | -0.646 |

| *Panel C: Plant-Level Variables* | *Fraction of obs. using equipment or HRM practices in 2002* | *Fraction of obs. adopting equipment or HRM practices bet. 1997 and 2002* |
|---|---|---|
| *FMS* | 0.337 | 0.151 |
| *Automated sensors* | 0.283 | 0.137 |
| *3d Cad* | 0.738 | 0.387 |
| *CNC (in use)* | 0.873 | 0.095 |
| *New CNC purchase (1997-2002)* | - | 0.736 |
| *Basic training* | 0.333 | 0.119 |
| *Technical training* | 0.726 | 0.211 |
| *Teams* | 0.647 | 0.298 |
| *Incentive Pay* | 0.312 | 0.118 |
| *Operator meetings* | 0.957 | 0.354 |

*1. In hours, except for Number of machines.*
*2. In hours, except for Number of machines.*

**Table 4**
**The Effects of IT on Process Innovation: [a]**
**Dependent Variables: Product-specific Production Times Across Plants**

| Dependent variable: | Percentage Change in Setuptime 97-02 | | Percentage Change in Runtime 97-02 | | Percentage Change in Insptime 97-02 | |
|---|---|---|---|---|---|---|
| Percentage Change in Machines 97-02 | **0.668*** (0.207)** | **0.699*** (0.206)** | **0.309** (0.180)** | **0.296* (0.181)** | 0.205 (0.228) | 0.207 (0.221) |
| Introduced Flexible Manufacturing (FMS) 97-02 | -0.049 (0.242) | | **-0.457** (0.215)** | | 0.215 (0.268) | |
| Introduced FMS and 3D CAD/CAM | | 0.051 (0.272) | | **-0.567*** (0.246)** | | 0.340 (0.292) |
| Introduced Automated Sensors 97-02 | -0.057 (0.281) | | 0.279 (0.240) | | **-0.712*** (0.315)** | |
| Introduced Autosens and 3D CAD/CAM | | 0.114 (0.292) | | 0.229 (0.253) | | **-0.798*** (0.317)** |
| Introduced Computer 3D CAD/CAM 97-02 | -0.008 (0.187) | | -0.266 (0.160)* | | -0.150 (0.209) | |
| | | | | | | |
| | | | | | | |
| Observations<br>R-squared | 165<br>0.10 | 163<br>0.11 | 159<br>0.20 | 157<br>0.193 | 168<br>0.06 | 166<br>0.06 |

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

**Table 5**

**The Effects of HRM on Process and Product Innovation [a]**

**Dependent Variables: Product-specific Production Times Across Plants**

| Dependent Variable: | Percentage Change in Setuptime 97-02 | Percentage Change in Runtime 97-02 | Percentage Change in Insptime 97-02 |
|---|---|---|---|
| Percentage Change in Machines 97-02 | **0.766***<br>(0.227)** | 0.353<br>(0.202) | 0.180<br>(0.229) |
| Introduced Flexible Manufacturing 97-02 and 3D CAD/CAM | 0.226<br>(0.313) | **-0.579***<br>(0.288)** | 0.461<br>(0.317) |
| Introduced Automated Sensors 97-02 and 3D CAD/CAM | 0.104<br>(0.336) | 0.228<br>(0.295) | **-0.966***<br>(0.338)** |
| Training Introduced 97-02 | **-0.507***<br>(0.242)** | -0.270<br>(0.208) | **-0.484**<br>(0.243)** |
| Observations | 145 | 140 | 149 |
| R-squared | 0.14 | 0.22 | 0.10 |

Standard errors in parentheses

*Significant at 10%; ** Significant at 5%; *** Significant at 1%

[a] These regressions include controls for age of plants, number of shopfloor workers, and dummy for unionization

**Table 6**

**The Effects of IT on Changes in Batch Size, 1997-2002 [a]**
**First Difference Regressions**

| | Percentage Change in Batch Size, 1997-2002 | Batch Size Down[b] 1997-2002 | | |
|---|---|---|---|---|
| Percentage Change in Machines 1997-2002 | 0.709***<br>(0.191) | -0.223***<br>(0.085) | -0.267***<br>(0.094) | |
| High New IT[c] | | | 0.235***<br>(0.087) | 0.206***<br>(0.081) |
| N<br>R-squared | 157<br>0.088 | 176<br>0.043 | 174<br>0.071 | 174<br>0.045 |

Standard errors in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%

*a* -- All regressions include controls for age of plant, number of shopfloor workers, and dummy for unionization

b – Dependent variable is dummy variable if batch size fell from 1997 to 2002 (mean value of .58). Regression is estimated as probit evaluated at the mean, and the R-squared is the pseudo-R-squared.

c – "High New IT" is defined as a dummy variable =1 if the plant adopts two of the three following IT-based production technologies: (new CNC, FMS, or automatic sensor inspection) and 3D CAD/CAM

**Table 7**
**Determinants of Entry and Exit in the Valve Industry Between 1992 and 1997 [a]**

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

[a] Probit coefficients (evaluated at the mean) and standard errors in parentheses.
* - Significant at 10% level; ** - significant at 5% level; *** - significant at 1% level.
A NEW ENTRANT is a dummy variable if the plant entered the industry from 1997-2002; EXIT is a dummy variable if the plant left the industry, 1997-2002
PPSR is the Primary Product Specialization Ratio at the 7-digit industry level.

**Table 8**

**The Adoption of New HRM Practices Between 1997 and 2002 (Probit Estimates)[a]**

| Dependent variable | New HRM Index[b] | | High New HRM Index[c] | |
|---|---|---|---|---|
| New IT Index[d] | 0.415***<br>(0.080) | 0.396***<br>(0.084) | 0.233***<br>(0.061) | |
| High New IT Index[e] | | 0.071<br>(0.107) | 0.200***<br>(0.096) | 0.285***<br>(0.100) |
| Big (employees>50) | 0.233***<br>(0.103) | 0.236***<br>(0.103) | 0.185***<br>(0.071) | 0.191***<br>(0.072) |
| Shop employees | -0.0009*<br>(0.0005) | -0.0009**<br>(0.005) | -0.0003<br>(0.0004) | -0.0002<br>(0.0004) |
| Age plant | -0.0020<br>(0.009) | -0.0022<br>(0.0019) | -0.0046**<br>(0.0017) | -0.0044***<br>(0.0017) |
| Union | .132<br>(0.102) | .131<br>(0.103) | .099<br>(0.099) | .105<br>(0.099) |
| Log likelihood<br>N<br>Pseudo $R^2$ | -102.4<br>167<br>0.115 | <br>165<br>0.112 | 165<br>0.149 | 165<br>0.107 |

a. Probit coefficients (evaluated at the mean) and standard errors are presented.
b. New HRM Index=1 if plant adopts one of the HR practices -- new teams, new meetings, or new training programs.
c. High New HRM Index = 1 if plant adopts two of the three HR practices – teams, meetings, or new training.
d. New IT Index = 1 if plant adopts one of the three new IT technologies – new CNC, FMS, or auto sensors
e. High New IT Index = 1 if plant adopts two of the three new IT technologies – (new CNC, FMS, or auto sensors) and 3D CAD/CAM

**Table 9**
**The Effects of IT on Importance of Different Types of Skills [a]**
**Dependent Variable: Equals One if Skill's Importance Increased Between 1997 & 2002**

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| | New Tech Skills[e] | Math | Computer | Programming | Problem -Solving | Computer and Problem-Solving | Cutting Tools | Multiple Machines |
| **<u>IT Measure for:</u>** | | | | | | | | |
| **Regression 1:** “New IT Index,” 1997-2002[b] | 0.256*** | 0.128 | 0.182*** | 0.293*** | 0.138* | 0.236*** | 0.246*** | 0.088 |
| | (0.084) | (0.087) | (0.085) | 0.085) | (0.085) | (0.083) | (0.084) | (0.088) |
| Pseudo-$R^2$ | 0.074 | 0.024 | 0.027 | 0.071 | 0.021 | 0.039 | 0.032 | 0.022 |
| **Regression 2:** “New IT Index,” 1997-2002 [b] | 0.159*** | 0.118 | 0.136** | 0.312*** | 0.166** | 0.242*** | 0.233*** | 0.084 |
| | (0.082) | (0.091) | (0.086) | (0.087) | (0.090) | (0.086) | (0.088) | (0.092) |
| “High New IT Index,”1997-2002[c] | 0.178*** | 0.078 | 0.211*** | -0.011 | -0.078 | 0.037 | 0.034 | -0.052 |
| | (0.056) | (0.092) | (0.068) | (-0.096) | (0.091) | (0.093) | (0.093) | (0.094) |
| Psuedo-$R^2$ | 0.080 | 0.03 | 0.057 | 0.075 | 0.026 | 0.039 | 0.030 | 0.027 |
| Sample Size | 194 | 199 | 198 | 194 | 198 | 198 | 198 | 195 |
| Means | 0.78 | 0.57 | 0.71 | 0.53 | 0.68 | 0.50 | 0.52 | 0.59 |

Probit coefficients (evaluated at the mean) and standard errors are displayed.

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

[a] Each entry in this table reports the coefficients on the IT measures in 16 different regressions. All regressions include controls for age of plant, number of shopfloor workers, and dummy for unionization.

[b] New IT Index = dummy that equals one if plant added any one of the three pieces of IT equipment (new CNC, FMS, or Autosens).

[c] High New IT Index = dummy that equals one if plant added two of the three pieces of IT equipment (new CNC, FMS, or Autosens) and 3D CAD/CAM

[3] New Tech Skills are either math, computer, or programming.

## Appendix

Our survey dataset does not contain information on plant-level productivity; instead, we use data from the Census Bureau's Longitudinal Research Database to analyze the effects of investments in information technology and HRM practices on value-added, the typical plant-level productivity measure used in studies that rely on the LRD. We note that the impact of IT on value-added in the valve-making industry is likely to be ambiguous; a move to more customized products that sell at higher prices could be offset by cost increases due to higher setup-times for these products.

Using the LRD, we first estimate standard models of the effects of capital and worker skills on productivity and then compare results from these models to results obtained when productivity models are augmented with data from the survey tailor-made for the details of the valve makers' production process. In doing this, we address the concern raised by Griliches and Mairesse (1995) that "standard census type data do not provide enough additional information or relevant product and plant characteristics to allow one to pursue a substantive analysis."

We estimate a simple functional form for a production function, such as:

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

Where Q, K, L, and M are respectively the natural logarithms of output, capital input, labor input, and materials input so that (1) is just the ln-transformation of the Cobb-Douglas specification. Standard measures used from the LRD surveys are total value of shipments, gross value of depreciable assets, labor hours and cost of materials. If additional data on worker skills through education measures or through organizations' work practices such as teams or training programs (HR), then L in equation (1) can be modeled as some proportion of the reported labor input (RL) where the proportion varies with variables like an HR change according to:

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

(3) $\ln Q = a + b_4 * \ln K + b_5 * \ln RL + b_6 * \ln M + b_7 * HR + e_2$

We identified the plants in the LRD for 1997 and 1992 that match the sample of plants in our own survey using address and name matches[21] and estimate (1) with the 1997 LRD data for this sample of plants (n=178). We then estimate (10) using the same data but including our own

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

survey's measure for the presence of three HRM practices: a basic training program, a training program in new technical skills, and the presence of problem-solving teams. Finally, equations (2) and (3) are re-estimated in first-difference form for the 1992-1997 time period. The results are shown in Appendix Table A-1 where we observe that, while labor and materials inputs are significant in both the OLS and first-difference specifications, the capital input is insignificant.

The insignificance of the capital input is similar to what others have observed even when using the full sample of plants in the LRD (Black and Lynch, 2001) and is generally attributed to measurement error (e.g. if plant and property expenditures are important parts of the capital variable but relatively uncorrelated with output variation) or endogeneity bias. We are able to deal with the measurement error problem by using a direct measure from our own industry-specific survey – namely the number of CNC machines that the plant had in place in 1997. This is a more appropriate measure of capital for this industry because it identifies the actual number of machines that are a fundamental part of the production process. When we replace the LRD capital measure with this measure, we find a positive and significant coefficient in the levels equation (see column (2)) but not in the first-difference equation where the capital input is measured as the number of CNC machines introduced between 1992 and 1997.[22] Finally, when we include the three HR measures in the equation, we find a positive and significant effect of the presence of problem-solving teams, but not training, in the first-difference specification.

The weak effects of IT on value-added in 1997 may be due to several factors. First, the data are from 1997 and the introduction of IT-intensive CNC machines in the valve-making industry took place largely after 1997. An analysis using 2002 LRD data might reveal more significant effects of IT. Second, as explained above, value-added may not be an appropriate dependent variable.

[22] The introduction of flexible manufacturing systems or automated inspection sensors between 1992 and 1997 also have insignificant effects in the 1992-1997 first difference model.

**Appendix Table 1**
**LRD Productivity Regressions[a]**

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

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