The Role of Information Technology in Modern Production: Complement or Substitute to Other Inputs?

February, 1999

Lorin M. Hitt
University of Pennsylvania, Wharton School
lhitt@wharton.upenn.edu
1318 Steinberg Hall-Dietrich Hall
Philadelphia, PA 19104

Eli M. Snir
University of Pennsylvania, Wharton School
eli@grace.wharton.upenn.edu
1300 Steinberg Hall-Dietrich Hall
Philadelphia, PA 19104

We would like to thank Erik Brynjolfsson, Eric Clemons, Rachel Croson, David Croson, Paul Kleindorfer, Moti Levi, Hank Lucas, and seminar participants at the Wharton School and the Workshop on Information Systems and Economics for comments on earlier drafts of this paper. This research has been generously supported by the National Science Foundation (Grant IIS-9733877). Incon Research, the Center for Survey Research, Computer Intelligence Infocorp and Informationweek provided or helped to collect essential data.

Currently Under Review for Management Science

The Role of Information Technology in Modern Production: Complement or Substitute to Other Inputs?

Abstract

Previous work has shown that the economic impact of IT in general varies systematically with the way a firm is organized. This study investigates the effect of organizational factors on a particular aspect of the economics of IT: the substitution of IT capital for other inputs such as ordinary capital and labor. Much of the previous discussion of IT impact has focused on the substitution of IT for labor, yet much of the managerial literature has recently stressed the importance of finding complementarities between IT and other organizational practices. The ability to identify and leverage potential complements between IT and other factors may become increasingly important as IT investments are used less for simple cost reduction and more for creating customer value. Using firm level data for over 400 large firms, we find that a firm's ability to complement existing capital with IT investments is dependent on organizational factors. For "modern" organizations, exemplified by a decentralized organizational form, greater use of skilled staff, newer capital investments, and less inventory, IT and capital are complements, while for their "traditional" counterparts they are substitutes. Also, we find that all forms of organizations use IT as a net substitute for labor. As the price of information technology continues to decrease, we expect firms that have the ability to capitalize on complements with other inputs to become more profitable. Our results suggest that the ability to complement other investments with IT is not limited to certain sectors, but does depend on appropriate organizational design that includes adoption of modern practices.

I. Introduction

The mechanisms by which information technology (IT) creates business value have been debated for over 40 years, starting with Leavitt and Whistler (1958). This paper examines one way in which IT creates value by complementing or substituting for other production inputs. For early IT applications, the value was generally viewed in terms of labor substitution; by using computers an organization could automate data storage and retrieval, conduct routine transaction processing and improve organizational communications. This reduces the need for file clerks, accountants and even middle managers, who traditionally performed those functions. Later, massive computerization of factories and equipment-intensive service operations (e.g., package delivery, air transport) created value by substituting capital. For example, computer-based scheduling and routing enabled transport vehicles to be used more effectively, reducing the need to expand fleets. Manufacturing automation systems boosted efficiency and utilization of existing facilities, permitting slower construction of new plants. Innovations in utilizing information for supply chain management have made possible substantial reductions in raw materials and finished goods inventories.

Recently, the emphasis in IT investment has shifted away from cost saving projects toward new ways of creating business value. Recent surveys of IT managers have revealed that cost saving is no longer the primary concern in their technology strategy. Enhancing other aspects of the business by improving time to market, quality, customer service and other intangible, revenue enhancing projects now appear to be the driver of new technology investments (Brynjolfsson and Hitt, 1996). However, as organizations have moved to pursue these strategies, researchers have increasingly recognized that IT investments must be accompanied by concurrent changes in other aspects of the organization (Hammer 1990; Davenport and Short 1990; Drucker 1988; Malone and Rockart 1991; Applegate, Cash and Mills 1988; Brynjolfsson and Mendelson 1993). The interaction between organizational design and the use of IT appears to be a critical part of IT investments. We examine this interaction by measuring the effect of organizational factors on the use of IT as a complement or substitute to other inputs.

As IT investment is increasingly directed toward organizational transformation rather than simple automation, new computers may become less of a substitute for other production inputs. Multiskilled, empowered production workers may be less likely to be replaced by a new computer than a file clerk would have been; "intelligent" machines linked together in a computer integrated manufacturing system (CIM) may be more valuable than these machines operated in isolation. Instead of being substitutes for traditional factors of production, computers may increasingly be complements, at least in some types of organizations and for some types of factors.

Numerous authors have argued that computers are complements to skilled, empowered workers, customer focused strategies and flexible production processes (Bresnehan, 1997; Drucker 1988; Applegate, Cash and Mills 1988; Brynjolfsson and Hitt, 1996; Brynjolfsson and Hitt, 1998)[1]. Milgrom and Roberts (1990) have formalized and summarized many of these arguments in a mathematical model. They argue that computer-aided design and computer-controlled equipment are *complementary* to a set of organizational practices which include: faster product cycles, flexible machinery, short production runs, reduced inventories, empowered employees, highly skilled staff, and improved integration with suppliers and customers. This argument implies that, as the price of computers declines (as has happened for the last 30 years) organizations will increase investment not only in computers but in other complementary factors as well (e.g., flexible machinery, skilled workers). While the Milgrom and Roberts model is motivated by changes that are occurring in manufacturing, the types of organizational practices they describe are generally applicable across a wide range of organizations. Similarly, researchers are beginning to build links between the logic of complementarities and reengineering by offering new methods of productivity enhancement that rely heavily on both computers and organizational changes (Brynjolfsson, Renshaw, and Van Alstyne, 1996; Barua, Lee and Whinston, 1996).

These arguments raise the possibility that IT may not be a substitute but instead a complement to traditional production factors such as capital and labor in organizations that have flexible production, empowered workers, skilled staff, and low inventories. For purposes of discussion, we will term this collection of organizational characteristics "modern" organization, paralleling Milgrom and Roberts' description of modern manufacturing.

In this paper, we explore the hypothesis that modern organizations exhibit more complements between IT and traditional production factors, capital and labor. We use data on organizational characteristics and production inputs and outputs for over 400 large firms over 8 years (1987-1994) and factor input and output data for as many as 1000 firms. The results indicate little difference between the propensity of IT to substitute for labor between modern and traditional organizations, but an increased complementarity between IT and capital in modern organizations.

These results suggest that there are fundamental differences in the role of IT in different types of organizations. Moreover, the robust IT-labor substitution result suggests that even in applications where IT is skill enhancing, it may lead to a net reduction in total labor demand. These results shed new light on the relationship between IT investment and other organizational characteristics providing additional insight on the mechanism by which IT leads to higher productivity .

The remainder of this paper is structured as follows: Section II reviews previous literature on organizational implications of IT and IT-factor substitution, generating hypotheses to be tested; Section III introduces the data and measurement framework; Section IV contains the results, and we conclude with a summary and discussion in Section V.

II. Previous Literature

While the possible effects of IT on organizations are quite large and varied[2] , in this section we focus specifically on arguments about how organizational practices can influence the degree of substitutability between IT and capital or IT and labor. We discuss previous work on the

---

1 IT has also figured prominently in arguments about the emergence of modern work practices (Ichnioski, Kochan, Levine, Olson and Strauss,1996), skill-related wage inequality (Autor, Katz and Krueger, 1997; Berman Bound and Griliches, 1994), and flexible production (MacDuffie, 1995).

2 A comprehensive discussion can be found in Lucas (1997) or other introductory texts.

estimation of the degree of substitution between IT and other production factors that underlie our modeling methods. Finally, we present the specific hypotheses that we test in Section III.

II.A. What is a Complement?

The notion of production complements is first attributed to Edgeworth (1938). In his definition, two factors are complements if an increase in the level of one factor raises the marginal value of another factor. One implication is that factors that are complementary tend to appear together: more of one is optimally accompanied by more of the other. In addition, a decline in the price of one of the complementary factors leads to increased use of both the factor and its complement. This is in contrast to the traditional notion of *substitution*; as the price of a factor declines, one uses more of that factor and less of other factors for which it is a substitute (see Allen, 1953, for the properties of this formulation).[3] The technical details of substitution measurement will be explored further in Section III.

II.B. Complementarities between IT and Labor

In the mid-1980s, a number of authors proposed new work systems in contrast to the traditional "mass production" style of organization that dates back to the beginning of the industrial revolution. New types of organizations such as flexible specialization (Piori and Sabel, 1984), high performance work systems (MacDuffie, 1995; Ichniowski, Prennushi and Shaw, 1996), and lean production (Womack, James and Roos, 1988) appeared. These general principles have also been examined by others in broader samples of the economy (Osterman, 1994; Huselid, 1994) and in more narrowly defined industries (Kelley, 1994). The exact description of these practices varies, but the practices themselves generally involve a combination of flexible machinery, skilled employees, and increased delegation of authority to line workers ("empowerment"), either through teams or through increased individual discretion.

Recent authors have recognized that information technology is a potential enabler of these types of work organization. Milgrom and Roberts (1990) cite CAD systems and manufacturing automation as being complements to these types of work practices. Brynjolfsson, Renshaw and

Van Alstyne (1996) describe a case where new flexible production technologies failed to meet expectations in terms of productivity improvements until they were coupled with increased delegation of authority and a team-based production structure. Lucas (1995) describes the “T-form organization” in which computers and communication networks are integrated with decentralization of decision rights to line workers to improve organizational performance. Ichniowski *et al.* (1996) cite IT as a potential barrier to the diffusion of workplace innovation. Despite high productivity gains possible by these work practices, diffusion may be slowed because of the need to make complementary investments in information technology. Kelley (1994) shows that the value of computer controlled machinery increases with flexible work practices. Numerous other authors have considered the notion of IT-skill complementarity as a potential explanation for rising differences in wages between high-school and college-educated workers (Autor, Katz and Krueger, 1998; Krueger, 1993; Berman, Bound and Griliches, 1994).

There are at least two possible explanations for a complementarity among decentralized organizations, skilled employees and IT. The first arises from the need to utilize specific knowledge better (Hayek, 1945). Through communications technologies and expert systems, line workers can be provided with the necessary information as well as analytical support to take action on specific information that they might possess by virtue of their direct contact with customers or the production process (Fisher *et. al*., 1994; Brynjolfsson and Mendelson, 1993). Second, IT may increase the demand for information processing, creating information overload on key decision makers (Simon, 1976; Brynjolfsson, 1994). An organization can expand its ability to process information by delegating authority to line workers (Brynjolfsson and Mendelson, 1993) or by building lateral communication links to enable individual decision makers to be more effective (Galbraith, 1977).

Both these reasons suggest that IT is more complementary to higher skilled labor and those employees who possess high levels of decision authority. For tasks that can be easily codified through rules or require relatively low level cognitive skills (information retrieval and storage), IT can be used to substitute for labor via automation.

---

[3] Technically, the two definitions of complements are not identical. However, showing that two inputs are *p-complements*, as defined by Allen (1953), is sufficient for those inputs to be *q-complements*, as defined by Hicks

II.C. Complementarities between IT and Capital

There has been a substantial increase in the use of manufacturing and service process automation over the last twenty years in the form of flexible manufacturing (FMS), materials resource planning (MRP I), manufacturing requirements planning (MRP II), computer integrated manufacturing (CIM) and now enterprise resource planning (ERP). Many of these flexible production technologies involve embedded computing or other forms of numerical or computer controls. This suggests that technical complementarities exist between general purpose computing and flexible manufacturing. For example, automatic production facilities incorporate FMS systems together with computer based scheduling and routing to achieve optimal production.

Many authors, however, have noted that computer technology-intensive production processes are often combined with changes in organizational design, different product strategies and computer-based control and monitoring systems (Milgrom and Roberts, 1990; Piore and Sabel, 1984; MacDuffie, Suthuraman, and Fisher, 1996; Corder, 1997; Sarkis, 1997). For instance, at MacroMed (Brynjolfsson, Renshaw and VanAlstyne, 1997) investment in flexible machinery was also accompanied by numerous changes in work systems (team production), incentives (elimination of piece rates), reduction in inventories and an substantial increase in product line breadth, This type of complementarity is more pervasive, representing a group of new organizational practices rather than simple technical linkages between different types of equipment. Firms that already have some of these elements in place (e.g. computer infrastructure, technology-enabled decentralized organizational forms) may find greater benefits from increasing investment in newer capital.

These complementarities may explain both the rapid diffusion of ERP technology and the difficulties many firms have in implementation. For instance, the SAP R/3 system, the most popular ERP system, is installed in over 13,000 sites, and SAP boasts that they have installations

(1970), which closely follows the Edgeworth definition.

at 70% of the Fortune 500 (SAP annual report, 1998). However, there are numerous reports of implementation failures and even litigation (e.g. Foxmeyer's lawsuit against Andersen Consulting) resulting from both the technological and organizational complexity of implementing these systems.

Complements between IT and physical capital are not limited to manufacturers. In the transportation industry, heavily dependent on physical capital, IT investments are becoming increasingly important. In the airline industry, computers have become a necessity for many parts of operations and marketing. From the operations perspective, modern, computer based, operation research techniques are crucial in developing flight plans and assuring coordination among airplanes, maintenance, crews and airports (e.g., Subramanian *et al* 1994; Anbil *et al*, 1991). From the marketing perspective, computers play a crucial role in yield management programs that have greatly increased airline profitability (e.g., Smith *et al* 1992).

Apparel distributors are also finding IT and physical capital to be complements. In an industry where fashion changes yearly and demand cycles are short, industry leaders must be capable of offering a wide variety of products in a short time-window. Sport Obermeyer, a leader in fashion skiwear, has demonstrated the need for coordinating capacity planning through IT (Fisher *et al.*, 1994). Since the peak of the retail season is only two months, and production lead times may be over a year, it is crucial that distributors correctly plan capacity. By incorporating *accurate response*, which schedules high-predictability items at the beginning of the production cycle and allows modular production, the company was able to reduce costs of product line breadth, thus allowing it to compete aggressively on product variety (Fisher *et al.*, 1994). An important part of *accurate response* is the combination of an IT investment for planning and forecasting, and a capital investment in flexible manufacturing systems to minimize the cost of short production runs and high degrees of product variety -- a complementarity between IT investment and capital.

II.D. Previous Work on IT-Substitution

The substitution between factors inputs has a well established theoretical basis in the microeconomic theory of production (e.g. Varian, 1992) and there are a variety of empirical tools for assessing this relationship (Berndt, 1992). Historically, these tools have been used to investigate substitution relationships such as the substitutability of capital and labor (Zarembka, 1970) and the effect of energy prices on the demand for capital following the 1973 oil shock (Berndt and Wood 1975; Berndt, 1992). Only recently, however, have studies begun to isolate and investigate the role of information technology capital.

Berndt and Morrison (1992) used panel data on manufacturing industries from 1972-1986 and estimated a number of simple production relationships. They found that in some cases IT appeared and to be a net complement to labor (although the results varied substantially by industry). Using firm-level data, Dewan and Min (1997) found that at the median IT was a perfect substitute for both capital and labor (that is, factor quantities adjust in direct proportion to changes in relative prices). This result generally held when various sub-samples of industry, growth opportunities, size, and other factors were considered.

Complementarities between IT and modern practices have also been suggested as an explanation for the recent and relatively high marginal product of IT found in many studies on IT and productivity (e.g. Brynjolfsson and Hitt, 1996; Brynjolfsson and Hitt, 1998). These complementarities have yet to be fully documented.

II.E. Formal Statement of Hypotheses

We focus on testing two specific hypotheses regarding the interaction between organizational practices and factor substitution suggested by the earlier discussion:

Hypothesis 1) IT and Capital show a greater degree of complementarity in organizations that utilize "modern" organizational practices

Hypothesis 2) IT and Labor show a greater degree of complementarity in organizations that utilize "modern" organizational practices

The crux of our investigation relies on the definition of "modern" practices. For this analysis we will focus on four indicators of the “modern” organizational system:

Age of capital. Firms that utilize newer capital are much more likely to be using flexible production technology with embedded computer-based controls or other potential complements to IT. Older equipment is indicative of a mass-production orientation.

Decentralized work practices. Firms that allocate high levels of decision authority to their workers, utilize self-direct work teams, have team-based incentives and train their workers more extensively all suggest the use of modern production work practices. We examine both an overall index of these practices as well as specific practices (e.g. teams) that are indicative of decentralization. The index we use is based on previous work by Hitt (1996) and Hitt and Brynjolfsson (1997).

Human Capital. Modern production organizations are likely to employ more skilled workers as well as have a higher average level of skill and education in the work force. Specifically, we use the percentage of skilled blue-collar workers to identify a skilled labor force.

Inventories. A related consequence of flexible production is that work in process and finished goods inventories can be substantially reduced due to decreased need for production buffers. We thus believe that inventory levels are good indicators of whether a firm has made other complementary changes necessary to utilize flexible production.

Ideally, we would like to have a complete set of variables that characterize "modern" practices. However, due to data limitations, we are limited to certain indicators that may be representative (but not exhaustively cover) of the practices associated with modern production. This may not be a serious limitation for two reasons. First, since complementarities arguments suggest that all factors are complementary to each other, observing the behavior of one element of a complementary system may be representative of the behavior of the system. Since these practices are not selected in isolation, it may be more reasonable to consider them as representing a small part of an overall system of practices than as specific practice. Second, since we are going to examine these practices across many different sectors of the economy, the commonalties of modern production may be more evident in general, widely applicable measures (such as the use of skilled workers) than for more micro-level metrics more unique to a particular industry (e.g. changeover time on the production line).

III. Methods and Data

III. A. Development of Estimating Equations

In developing our estimating equations, we follow standard approaches in the microeconomic theory of production. Each firm in our sample is represented by a production function that relates the quantity of output, measured by value added, that the firm produces (*O*) to the inputs it consumes. In this analysis we will consider three inputs: computer capital (*C*), non-computer capital (*K*), and labor (*L*), all measured in constant 1990 dollars. In addition, we assume that overall productivity can be influenced by the industry (*i*) in which a firm participates as well as general effects over time (*t*). This yields:

$$O = F(K, L, C; i, t)$$

The requirements for the production relationship (*F*) are minimal: it is generally assumed to be continuous, weakly increasing in all inputs and quasi-concave (Varian, 1992). The most common functional form used in prior IT production work (see e.g. Brynjolfsson and Hitt, 1996), the Cobb-Douglas form, is not suitable for this analysis since it restricts the rates of substitution between factors (the quantity we want to measure) to be constant. A common form that allows variable rates of substitution as well as some other useful economic effects (e.g. economies of scale in the use of particular factors) is the transcendental logarithmic, or “translog”, function form (Christenson, Jorgenson and Lau, 1973). With three inputs, and allowing overall productivity to vary by time and year, this form yields the following equation to be estimated:

$$\log O_{itj} = \text{Const.} + I_{ij} + Y_{tj} + a_C \log C_{itj} + a_K \log K_{itj} + a_L \log L_{itj} + \beta_{CC}(\log C_{itj})^2 + \beta_{KK}(\log K_{itj})^2 + \beta_{LL}(\log L_{itj})^2 + \beta_{CK}(\log C_{itj})(\log K_{itj}) + \beta_{CL}(\log C_{itj})(\log L_{itj}) + \beta_{KL}(\log K_{itj})(\log L_{itj}) + \varepsilon_{itj}$$

Other functional forms could be chosen, and are indeed chosen by other authors. We rely on the translog form because it does not require non-linear estimation techniques (with the attendant problems of convergence and local minima), provides a reasonable approximation to an arbitrary production relationship, and appears to have better performance in terms of capturing variation in the substitution elasticities than other possible functional forms.[4]

For production functions with more than two inputs, the most common measure of substitutability/complementarity is the Allen partial elasticity of substitution (AES). This is defined as the percentage change in the ratio of the quantity of two factors to the percentage change in their price ratio allowing all other factors to adjust to their optimal level. Often, these are estimated using factor prices and total costs to estimate a cost function, but these data are generally not available at the firm level. As suggested by Dewan and Min (1997), these estimates can also be performed using production functions instead of cost functions. For two inputs (in

[4] The translog functional form has the advantage of being flexible in the sense that it does not constrain substitution elasticities *a-priori*. However, once the functional parameters are determined using statistical methods, the frontier of possible elasticities is constrained. This is due to the monotonicity and quasi-convexity requirements of any production function. (See e.g. Caves and Christensen, 1980 for a theoretical discussion of this problem.) In our analysis we find that monotonicity and quasi-convexity requirements are met at the sample median, but not over the entire range of the data. This is a limitation of the functional form used.
The use of an alternative, non-linear, functional form may reduce the quasi-convexity violations, but would introduce additional estimation difficulties, such as multiple critical points. Berndt and Khaled (1979) used a generalized Box-Cox cost function and other constrained functional forms to estimate productivity in U.S. manufacturing between 1947-1971. Their findings suggest that several functional forms, including the translog, are dominated by the nonhomothetic, nonneutral generalized Box-Cox form. They also find that in estimating substitution elasticities for their data set, the differences between different functional forms are small and non-substantive. Thus, we are confident that partial elasticities of substitution based on the translog form are reasonable estimates.
A different flexible functional form used in previous work is the CES-translog, suggested by Pollack *et al.* (1984) and used extensively by Dewan and Min (1997). The main advantage of this functional form is that it may reduce violations of the regularity conditions of any production function, while the translog form violates these assumptions in approximately 75% of the observations (see Dewan and Min, 1997; results available from the authors). A key disadvantage of the CES-translog that has deterred us from choosing it is the fact that the structural form and non-linear estimation required impose severe constraints that result in substitution elasticities close to 1 and very little variability in results across the sample.

this example we use IT and Capital) in a three input production function, for any arbitrary production function, the AES is given by:[5]

$$\text{AES } \sigma_{CK} = (Cf_C + Kf_K + Lf_L)\det(H_{CK})/[CK\det(H)]$$

where f_C denotes $\partial O/\partial C$, det(H) is the bordered Hessian determinant:

$$H = \begin{vmatrix} 0 & f_C & f_K & f_L \\ f_C & f_{CC} & f_{CK} & f_{CL} \\ f_K & f_{KC} & f_{KK} & f_{KL} \\ f_L & f_{LC} & f_{LK} & f_{LL} \end{vmatrix}$$

and H_{CK} is the C,K co-factor of the H matrix

The other partial elasticities of substitution (σ_{CL}, σ_{KL}) are defined analogously.

If the AES is approximately equal to 1, then two goods are "normal" substitutes. Intuitively, the ratio of the factor quantities adjusts exactly in proportion to changes in their relative prices. If the AES is zero, the prices of the two factors have no influence on their ratio (they are neither complements nor substitutes), while negative numbers indicate that the two factors are complements.

There are a few difficulties in estimating the AES that are important to note. Since the equations for the AES are non-linear functions of estimated parameters as well as the quantities of various factor inputs, there is no simple way to calculate standard errors of the estimates or to allow them to vary continuously as a function of some other parameter (e.g. organizational structure). We therefore divide the sample into two or three parts representing the different levels of the organizational variables and then estimate separate production functions. The parameter estimates and actual data are then used to calculate a distribution of possible values of the AES. Our first approach treats the estimated production parameters as fixed and utilizes the actual data

[5] The exact equations for are very complex and are omitted for the sake of brevity. Interested researchers may obtain the SAS code that outlines the calculation of substitution elasticities and other quantities of interest directly from the authors.

to generate the distribution of elasticities. A second utilizes bootstrapping to generate a series of production parameter estimates, which then can be evaluated at various sample points (e.g. the mean) for each sub-sample. Both are presented in Section IV.

These distributions of substitution elasticities for each sub-sample (e.g. modern and non-modern organizations) are then compared using distribution-free statistical tests, the simple median test and the Wilcoxon Rank Test.[6] If organizational characteristics have no influence on substitution elasticities, then the distributions of the AES should be the same across different organizational characteristic sub-samples. Any differences (either statistical or economic) will address our hypotheses that organizational characteristics influence the substitutability between IT and other factors.

III.B. Data

The data-set used for this analysis is a cross-sectional survey of organizational practices conducted in 1995 and 1996 matched to a panel of IT spending and production output and inputs over the 1987-1994 time period. Table 1 provides descriptive statistics of the data set. A brief description of each data source follows. A much more detailed analysis of these survey data can be found in Hitt (1996) and Hitt and Brynjolfsson (1997).

Computer Technology: The measures of IT use were derived from the Computer Intelligence Infocorp installation database that details IT spending by site for companies in the Fortune 1000 (approximately 25,000 sites were aggregated to form the measures for the 1000 companies that represent the total population in any given year). This database is compiled from telephone surveys that detail the ownership for IT equipment and related products. The focus is on general purpose computing such as mainframes and PCs, so it is not likely to capture all aspects that could be considered IT such as embedded microprocessors or other types of computer-controlled

[6] The median test simply compares how many observations in a second distribution are above the median of the first distribution, and then calculates the probability of this occurrence under the assumption that the means are equal. The Wilcoxon test compares the rank order of the data and calculates the probabilities based on how often one distribution point ranks above another. Using rank-tests to evaluate differences between sub-samples imposes ordinal valuation on cardinal data. To eliminate biases that may occur from over-weighing small differences, we recalculate the Wilcoxon Rank-test using threshold values to define conditions under which small differences are ignored. This has no impact on results.

machinery. Most sites are updated at least annually with greater sampling for larger sites. The year-end state of the database from 1987 to 1994 was used to calculate a total IT stock value which is then deflated to calculate computer capital in constant dollar terms.

Compustat. Compustat data was used to construct measures of ordinary capital, labor and output. For the calculation of factor inputs, we followed the procedures in Hall (1990) and Brynjolfsson and Hitt (1994). In addition, Compustat was the source of the age of capital (calculated as accumulated depreciation divided by current depreciation) and the inventory measure (total inventory/sales).

Organizational Practices: The organizational practices data were collected in three survey efforts over 1995 and 1996. This survey was prepared based on the organizational characteristics identified in prior literature, and adapted questions from prior surveys on human resource practices and workplace transformation (Huselid, 1994; Ichniowski, Shaw and Prunnushi, 1997; Osterman, 1994). Questions addressed the allocation of various types of decision authority, the use of self-managing teams, investments in training and education, incentives and promotion criteria, the extent of computerization and other miscellaneous characteristics of the workplace.

The survey was administered to senior human resource managers or their designees, and asked questions about organizational practices at the most typical establishments. The approach of Osterman (1994) was followed in focusing on a single class of employee termed “production employees” (which corresponds to Osterman’s “core employee”). A production employee was defined as “non-managerial, non-supervisory personnel directly involved in producing a firm’s product or delivering its service”.

Two variables are used from these data. First, we capture the percentage of the workforce who are skilled blue collar workers (indicative of the skill levels used for front-line workers). Second, we measure organizational decentralization, using a scale developed by Hitt and Brynjolfsson (1997) that captures a measure of decentralized work practices in three groups: individual decision authority, use of team and team-based incentives, and acquisition of human capital (screening for education and training). A single variable is constructed by the sum of standardized values of the component measures. This scale has good psychometric properties and broadly captures the extent to which an organization has higher levels of skill and decentralized decision authority (see the discussion in Brynjolfsson and Hitt (1997) and Appendix A for more detail on the construction of this scale, including the actual survey questions).

These data are available for 416 firms, although after matching the data to other data sources, we are left with 1,596 observations over 8 years representing 304 firms.

IV. Results

We begin by estimating a baseline regression and substitution elasticites for the entire sample as well as the sub-sample for firms with responses to the organizational practices survey. We then examine, in turn, the effect of four organizational characteristics: decentralized work systems, age of capital, human capital (composition of the work force) and inventory intensity on the AES between IT and labor and IT and capital. For each analysis, we divide the sample into three subsets and compare the elasticity of substitution across the various samples. We then examine other subsets of the data to gauge the robustness of the results to variation in the estimation method and variation in the treatment of industry-specific variation.

IV. A. Baseline

Table 2 reports the regression results for the translog model for both the entire sample and the sub-sample that has complete organizational characteristics. The output elasticites (proportional to the rate of return) of capital, labor and computers are 0.13, 0.73 and 0.11,[7] comparable to previous work on firm level production functions (Brynjolfsson and Hitt, 1995; Lichtenberg 1995; Dewan and Min, 1997) and all are significantly different from zero (p<.001). The high R^2 signals that this functional form captures a substantial portion of the variability in the sample.

[7] The estimated elasticities are similar for capital and labor to those reported in other papers (Brynjolfsson and Hitt, 1998; Lichtenberg, 1995). However, our elasticity of computers is somewhat higher; this appears to be due to our removal of some outliers. We retain this sub-sample since outlier removal is more critical for analysis of substitution elasticities where outlying points can have a large influence on the curvature (and therefore substitution elasticities) of estimated production functions.

The second order terms in the translog are significantly different from zero (F =72.839; p<.001), suggesting that the more general functional form is warranted for estimating substitution elasticities (while the estimates of output elasticities and marginal products of individual factors are close to Cobb-Douglas estimates, consistent with previous work). Evaluating the differences between the models shows that the parameter estimates in the sub-sample are similar to those of the entire sample, allowing us to use this sub-sample in further analyses of the data.

Table 3a reports median, inter-quartile range and 90% confidence intervals for the partial elasticities of substitution between IT and other inputs in the baseline model. These are calculated over the data points in our sample, while holding the parameters of the production function fixed. We also investigate the robustness of holding these parameters (which are estimates) fixed. As observed in previous analyses, we find that overall IT and Capital are nearly perfect substitutes ($\sigma_{CK}\approx1$ with an interquartile range of 0.422 – 1.294). This result is consistent with prior work on IT substitution (Dewan and Min, 1997). Substitution between IT and labor is also quite high, but these are not perfect substitutes, with $\sigma_{CL}\approx0.6$ (interquartile range is 0.534 – 0.801). Comparing the entire sample to the sub-sample, we find that at the median, the latter demonstrates a slightly higher rate of IT-Capital substitution and a slightly lower rate of IT-Labor substitution.

To gauge the robustness of our methodology further, we repeat this analysis holding the point in the sample fixed, but accounting for variance in the production function parameter estimates through bootstrapping[8]. The results for the mean inputs in the entire sample and the sub-sample are shown in Table 3b and are similar to our earlier estimates. These results provide further

---

[8] Bootstrapping is a technique for generating test statistics for parameters where the distributional properties are not known a-priori. The methodology is as follows: a) the production function is estimated by OLS for each sub-sample to obtain the empirical distribution of the error term, b) the actual observations of the dependent variable are replaced with fitted values from this regression plus a random draw from the empirical error distribution, c) the regression is rerun using these new dependent variable values, and d) steps c and d are repeated (in our case 10,000 times) to generate a series of parameter estimates. These parameter estimates are then used to calculate substitution elasticities. This yields much more stable and plausible estimates of the elasticities than simulating a parameter vector through random draws of a normal distribution based on the initial regression, and requires no a-priori assumptions about the true distribution of the parameters.

support for the claim that, economy-wide, IT is a substitute for other production inputs such as Capital and Labor.

IV.B. Comparing Substitution Effects Across Different Types of Firms

The baseline model provides us with evidence of overall substitution behavior of IT and other inputs. To test the hypothesis that interactions exist between organizational parameters and the extent of substitution between IT and capital or labor, we divide the sample into three approximately equal size sections representing differences organizational parameters and compare the lowest and highest third. We split the sample based on four variables: organizational form, average age of capital, workforce composition (percent of skilled blue collar workers), and inventory intensity. For each sample split, we compare the input substitution for the firms in the top third with that of firms in the bottom third. This provides the starkest difference between modern and traditional firms and is robust to moderate amounts of measurement error in the variables that define the sample splits.

The main results of these sample splits are summarized on Table 4 and presented graphically as box plots in Figures 1 and 2. Reading across the table, we find that the sub-samples that correspond to our description of modern organization show a consistently greater degree of complementarity between IT and Capital than those who are more traditional, but a similar, if not greater, degree of substitutability between IT and Labor than traditional firms. The greatest contrast appears in workforce composition for the Computers - Capital (C-K) substitution elasticity. Firms with skilled workers have strong C-K complements (σ_{CK} = -1.3), while firms with more unskilled workers exhibit substitution between IT and Capital (σ_{CK} =.8). The IT-Labor substitution effects are similar between sub-samples except for the large difference (.4 vs. 1.3) for the capital age split. Interestingly, in some instances (e.g. the decentralization split), we cannot reject the hypothesis that traditional firms have a *Cobb-Douglas* production function. This suggests that traditional firms have a more straightforward production process than those in the modern sub-sample.

These differences are easily visualized by the box plots in Figure 1. The box plots show the median substitution elasticity in each sub-sample, as well as the interquartile range of elasticities. These plots clearly show that the relationship between production factors is very different between the two sub-samples (Figure 1) providing stark support for the first hypothesis. From the contrast in IT-Capital substitution between organizational forms it is evident that IT investments are more complementary to Capital in modern organizations across all four organizational measures. Figure 2, however, does not support the second hypothesis, since it shows that IT investments substitute for labor in all types of organizations.

IV.C. Robustness of Empirical Results

The results above definitely identify differences between the organizational sub-samples. In this section, we test the robustness of these results by relaxing various assumptions on how the samples and distributions are measured. In addition, we examine one plausible alternative hypothesis: that variation across industries is driving our results. We also performed a number of additional robustness tests as described in footnote 9.

Median Splits. Table 5 shows the results of splitting the samples at the median rather than in thirds for each of our four organizational parameters. The differences are similar although there is less contrast. In modern firms the degree of complementarity between IT and Capital is still greater for all four measures, we again find no consistent differences in IT-Labor complementarity. This suggests that our results are largely insensitive to the choice of sample split.

Bootstrapping. We repeated our base analyses using bootstrapping, evaluating the data at the sample mean. These results are shown in Table 6. Again, as with the population results shown in Table 3b, these results are robust in accounting for variance in the parameter estimates. All differences found earlier are also present and highly significant (p<.001) in all four sample splits.

[9] Our results also hold when we restrict the data to the 1994 cross-section alone or estimate a “between” estimator where the production inputs are averaged over time to create a single cross-section of data.

Accounting for Industry Variation. While our data set is not large enough to provide robust estimates of the substitution effects in different industries, we are able to examine whether our results are driven by industry heterogeneity. First, we examine whether defining the sample splits within industry rather than across the industries makes a difference. If some industries have disproportionately high (or low) values of the various modern organization indicators, we may have falsely confounded industry-specific variations in production processes with “true” effects due to variation in organization.[10] Table 7 reports the result of splitting the sample within each industry, for each of the four organizational parameters. Overall, while there is some movement of the degree of substitution/complementarity on the traditional firms across industries, modern organizations consistently show greater complementarity between IT and Capital and about the same degree of IT-Labor substitution, reinforcing our previous results.

We probe this result in another way by subdividing the sample by broad industry groups. We repeated our base analysis, first restricting the sample to manufacturing, and then extending it to all non-financial services. We show the results when our sample is limited to manufacturing firms in Table 8; this is not materially different from the results for non-financial firms. These results are again consistent with our previous results, suggesting again, that the effects we observe are apparent both within as well as between industries.

V. Discussion and Conclusion

V. A. Discussion

The use of IT to create business value is of prime concern. We hypothesize that the use of IT is not consistent among organizations and these systematic differences may have implications for how well a firm can capitalize on the long-run declines in the price of IT. A consistent result throughout this analysis is that organizations with modern practices have a much greater degree of complementarity between IT and Capital, but a similar degree of IT labor substitution. The observation of differences in complementarities between IT and Capital is consistent with the idea, that is prevalent in the work organization literature, that there are at least two clusters of

[10] The industry variation is itself interesting, since some industries may be "leaders” or “laggards” in shifting to new types of production systems. However, our analysis would be more convincing if it were not driven by industry

organizational practices with different fundamental properties: traditional organization, based on concepts of mass production, and modern organization which is characterized by flexible machinery, newer capital, skilled workers, lower inventories and greater decentralization of decision rights to line workers. We show these differences by analyzing the AES between inputs in modern and traditional organizations.

Our results can explain recent observed trends in the rapid adoption of ERP systems and the general trend in the U.S. economy of accelerating capital investments (see e.g. Economic Report of the President, 1998). While the increase in capital is often attributed to a rise in IT spending, the amount invested in computers even today is still relatively small compared to the magnitude of other investments (by most estimates IT represents about 10% of capital spending in current dollar terms). However, if computer investment increases the profitability of capital investment because of complementarities then the benefits of computers to productivity can be greatly magnified. The recent interest in ERP systems is the most recent manifestation of this trend toward IT-capital complementarities which is the culmination of more than 20 years of progress in linking information technology to basic manufacturing technology.

The labor result is somewhat more perplexing. One explanation, that is not inconsistent with the modern manufacturing concept, is that IT increases demand for certain labor skills (IT-skill complementarity), yet the skilled labor complementarity does not outweigh the substantial ability of IT to substitute for relatively low-skill, routine tasks. In many of the classic reengineering stories (Hammer, 1990; Davenport and Short, 1990) large staff reductions can simultaneously be accompanied by increases in skill and responsibility for those employees who remain. For instance, the Ford Accounts payable reengineering project greatly increased the responsibility of the 125 workers who remained in the department, but also led to the elimination of 500 jobs. Even within modern organizations, while IT is a complement to a small segment of the workforce, there is still a large component of the workforce that is susceptible to IT substitution.

---

alone.

An alternative story is that organizations that are more decentralized have more staffing flexibility and are therefore better able to take advantage of more IT-labor substitution possibilities. Without detailed data on workplace skill[11], it is difficult to identify this effect by using the approach developed here, but this explanation would reconcile these results with evidence of a complementarity between IT and skill that has been identified in the literature on wage inequality (Krueger, 1993; Autor, Katz and Krueger, 1997; Bresnehan, 1997). While IT is a complement to skill, being able to realize these IT-skill complementarities may require organizational restructuring and staff reduction, which is easier to accomplish in modern organizations

A second possibility is that another aspect of the modern manufacturing system, the increased reliance on suppliers and outsourcing, can cause the appearance of labor substitution. There is theoretical and empirical evidence that IT investment is associated with decreased vertical integration and increased reliance on outsourcing (Hitt, 1998; Brynjolfsson, *et al.*, 1994; Clemons, Reddi and Row, 1993). If reduced staffing, accompanying decreased integration, is prevalent in modern organizations, we would see IT-labor substitution in such organizations. However, regardless of which interpretation is true, our results suggest that even as firms shift toward using modern technology and empowered workers, we still expect IT investment to be associated with workforce reduction.

V.B. Extensions

The use of firm level data inhibits us from evaluating micro-level substitution between different inputs. While we find no evidence of complements between IT and labor, this may be a result of the resolution of our data. Claims of IT-labor complements describe the use of computers to enhance performance of certain sectors of the workforce, such as software engineers, financial consultants and other knowledge workers. This analysis does not look at the impact of increased IT on these sectors independently of the net effect IT has on the workforce. More detailed data

[11] Our attempts to segregate labor into skilled and unskilled and estimate separate substitution rates was unsuccessful; the parameter estimates were too unstable to yield meaningful substitution elasticities.

on the use of computers and their effect on different sectors are required to properly answer this question.

Similar to IT-labor effects that are measured only at an aggregate level, IT-capital substitution and complements may vary depending on the type of physical capital evaluated. Our results show that modern producers use IT to complement and enhance their other investments, although we cannot say exactly which investments become more profitable as computing power increases. Although we would expect FMS and CIM to be highly complementary to general purpose IT investments (Milgrom and Roberts, 1990), the available data cannot describe the impact IT has on the transportation industry, for example.

The choice of the translog production function also poses some methodological difficulties. In our analysis the quasi-concavity requirement of any production function is violated for many observations in the sample. Other functional forms may be more applicable to this data, however we have not found a better function. The CES-translog, proposed by Pollak, Sickles and Wales (1984) and used by Dewan and Min (1997), has numerous local minima (it requires non-linear estimation) and shows an implausible absence of variation in substitution elasticity across the firms in our dataset.

V.C. Conclusion

Our results suggest that the role of IT as an input factor varies substantially across organizations, in a manner that can be interpreted using previous theoretical arguments. Firms that adopt modern organizational practices are much more likely to find IT a complement to capital, but no more (or less) likely to be able to substitute IT for labor. The result is robust across a range of estimation strategies and methods of characterizing organizations as “modern”.

At a minimum, these results clearly suggest that firms that adopt these modern organizational practices have a production relationship that is fundamentally different from those that continue with mass production style orientation. Moreover, as the opportunity for simple cost reduction with IT becomes exhausted, either because of declining marginal benefits or because cost reductions are easily emulated by competitors, firms that are poised to leverage their existing assets in new ways are likely to increase performance and find additional ways to exploit the ongoing improvements in the price-performance ratio of IT.

As the price of information technology continues to decrease, we expect firms that have the ability to capitalize on complements with other inputs to become more profitable. Our results suggest that the ability to complement other investments with IT is not limited to certain sectors, but does depend on appropriate organizational design that includes adoption of modern practices.

Tables

Table 1: Descriptive Statistics

	Median	Mean	Standard Deviation	Minimum	Maximum
Value Added[1]	817.9	1,758.7	3265.1	0.6	62,486.0
IT stock[1]	13.9	38.1	78.3	0.1	1,414.8
Non-IT Capital[1]	1,273.7	4,666.8	9,779.0	12.3	13,3342.2
Labor Expense[1]	472.3	1,031.6	1,993.5	5.4	43,212.6
Employees[2]	12.6	27.0	46.6	0.4	756.3

[1] Based on 4,782 Observations
[2] Based on 4,711 Observations

Table 2: Regression results for the baseline models

	Complete Sample	OrganizationalData Sub-sample
Constant	1.878*** (0.1390)	1.273*** (0.2812)
log(IT)	0.187*** (0.0400)	0.101 (0.0725)
log(Capital)	0.053* (0.0315)	0.173*** (0.0584)
log(Labor)	0.449*** (0.0515)	0.569*** (0.0995)
$log(IT)^2$	-0.021*** (0.0046)	-0.023*** (0.0084)
$log(Capital)^2$	0.0433*** (0.0032)	0.041*** (0.0057)
$log(Labor)^2$	0.070*** (0.0061)	0.069*** (0.0106)
log(IT)log(Capital)	-0.004 (0.0051)	-0.003 (0.0092)
log(IT)log(Labor)	0.010 (0.0093)	0.025 (0.0162)
log(Capital)log(Labor)	-0.086*** (0.0062)	-0.104*** (0.0105)
Dummy Variables	Industry, Year	Industry, Year
R^2	0.94	0.93
N	4,782	1,596

Key: *** $p<.01$, ** $p<.05$, * $p<.1$; Standard Errors in parenthesis

Table 3a: Partial Elasticities of Substitution - Baseline Models (variation across sample, holding estimates fixed)

	Complete Sample				**Sub-Sample Including Organizational Characteristics**			
	Median	IQR	5th Percent	95th Percent	Median	IQR	5th Percent	95th Percent
IT-Capital Substitution	0.945	0.872	-1.978	3.425	0.994	0.513	-0.579	2.826
IT-Labor Substitution	0.688	0.267	-0.031	0.991	0.632	0.251	-0.083	0.818

Table 3b Partial Elasticities of Substitution - Baseline Models (bootstrapping; estimated for mean firm inputs)

	Complete Sample				**Sub-Sample Including Organizational Characteristics**			
	Median	IQR	5th Percent	95th Percent	Median	IQR	5th Percent	95th Percent
IT-Capital Substitution	1.347	1.220	0.008	3.258	1.274	3.230	-3.695	10.485
IT-Labor Substitution	0.630	0.240	0.290	0.924	0.598	0.578	-0.825	1.517

Table 4: Sub-sample differences in substitution (three-way sample splits)

	Decentralization		**Capital Age**		**Workforce Composition**		**Inventory Level**	
	Low	High	Old	New	Non-Skilled	Skilled	High	Low
IT-Capital Substitution	0.307 (0.322)	-0.713*** (2.240)	0.397 (0.941)	-1.400*** (1.605)	0.756 (1.219)	-1.334*** (1.938)	1.016 (0.039)	0.367*** (0.512)
IT-Labor Substitution	0.735 (0.154)	0.900*** (0.635)	0.436 (0.524)	1.336*** (0.170)	0.717 (0.255)	0.829* (0.151)	1.064 (0.027)	0.760* (0.238)

Point estimate in each cell (interquartile range in parenthesis); sub-sample difference significance: *** - p<.001; ** - p<.01; * - p<.1

Table 5: Sub-sample differences in substitution (two-way sample splits)

	Decentralization		**Capital Age**		**Workforce Composition**		**Inventory Level**	
	Low	High	Old	New	Non-Skilled	Skilled	High	Low
IT-Capital Substitution	-0.143 (0.573)	-0.868*** (2.909)	0.641 (0.624)	-1.992*** (2.993)	-0.256 (2.349)	-0.523*** (1.312)	0.242 (0.576	0.547*** (0.187)
IT-Labor Substitution	0.836 (0.101)	0.789*** (0.679)	0.477 (0.423)	1.579*** (0.252)	0.755 (0.407)	0.588* (0.311)	0.907 (0.181)	0.905 (0.074)

Point estimate in each cell (interquartile range in parenthesis); sub-sample difference significance: *** - *p*<.001; ** - *p*<.01; * - *p*<.1

Table 6: Sub-sample differences in substitution (bootstrapping; estimated at mean firm inputs)

	Decentralization		**Capital Age**		**Workforce Composition**		**Inventory Level**	
	Low	High	Old	New	Non-Skilled	Skilled	High	Low
IT-Capital Substitution	0.300 (0.578)	-1.699*** (1.834)	-0.033 (0.707)	-1.179*** (0.916)	0.790 (0.848)	-1.33*** (1.320)	1.057 (1.560)	0.401*** (0.439)
IT-Labor Substitution	0.735 (0.281)	1.096*** (0.389)	0.567 (0.241)	1.293*** (0.338)	0.621 (0.154)	0.800*** (0.404)	1.069 (0.345)	0.750*** (0.207)

Point estimate in each cell (interquartile range in parenthesis); sub-sample difference significance: *** - *p*<.001; ** - *p*<.01; * - *p*<.1

Table 7: Sub-sample differences in substitution (within industry splits)

	Decentralization		**Capital Age**		**Workforce Composition**		**Inventory Level**	
	Low	High	Old	New	Non-Skilled	Skilled	High	Low
IT-Capital Substitution	-0.155 (0.560)	-0.545 (2.692)	0.642 0.638)	-0.820*** (1.038)	-0.086 (2237)	-2.047*** (2.123)	1.677 (2.584)	-0.14*** (0.847)
IT-Labor Substitution	0.630 (0.226)	0.719*** (0.399)	0.435 (0.483)	1.218* (0.190)	0.763 (0.259)	1.385* (0.153)	1.165 (0.490)	1.022 (0.088)

Point estimate in each cell (interquartile range in parenthesis); sub-sample difference: significance: *** - *p*<.001; ** - *p*<.01; * - *p*<.1

Table 8: Sub-sample differences in substitution (only Manufacturing firms)

	Decentralization		Capital Age		Workforce Composition		Inventory Level	
	Low	High	Old	New	Non-Skilled	Skilled	High	Low
IT-Capital Substitution	-0.154 (0.766)	-3.122*** (4.754)	0.004 (1.728)	-3.620*** (4.640)	2.045 (1.259)	-3.626*** (12.450)	-0.296 (0.595)	0.122*** (0.809)
IT-Labor Substitution	0.947 (0.067)	1.799*** 0.491	0.634 (0.470)	2.307 (0.621)	0.532 (0.559)	1.373*** (1.417)	0.882 (0.105)	0.775*** (0.642)

Point estimate in each cell (interquartile range in parenthesis); sub-sample difference significance: *** - p<.001; ** - p<.01; * - p<.1

Figure 1: IT-Capital Substitution across sample splits (Medians and Quartiles Shown)

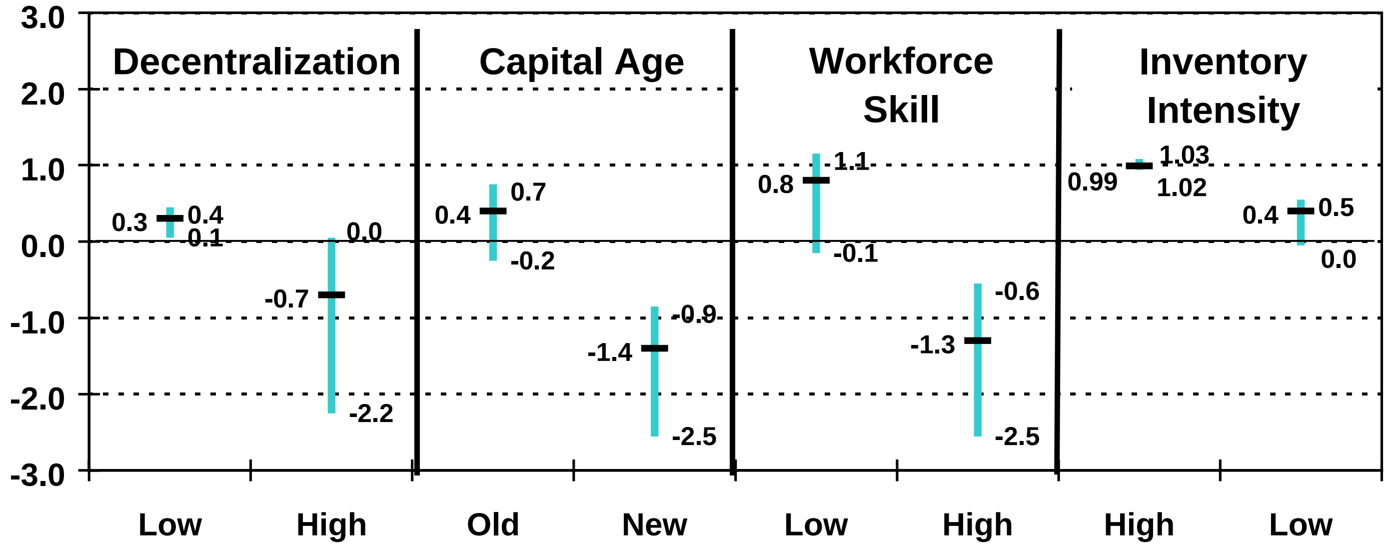
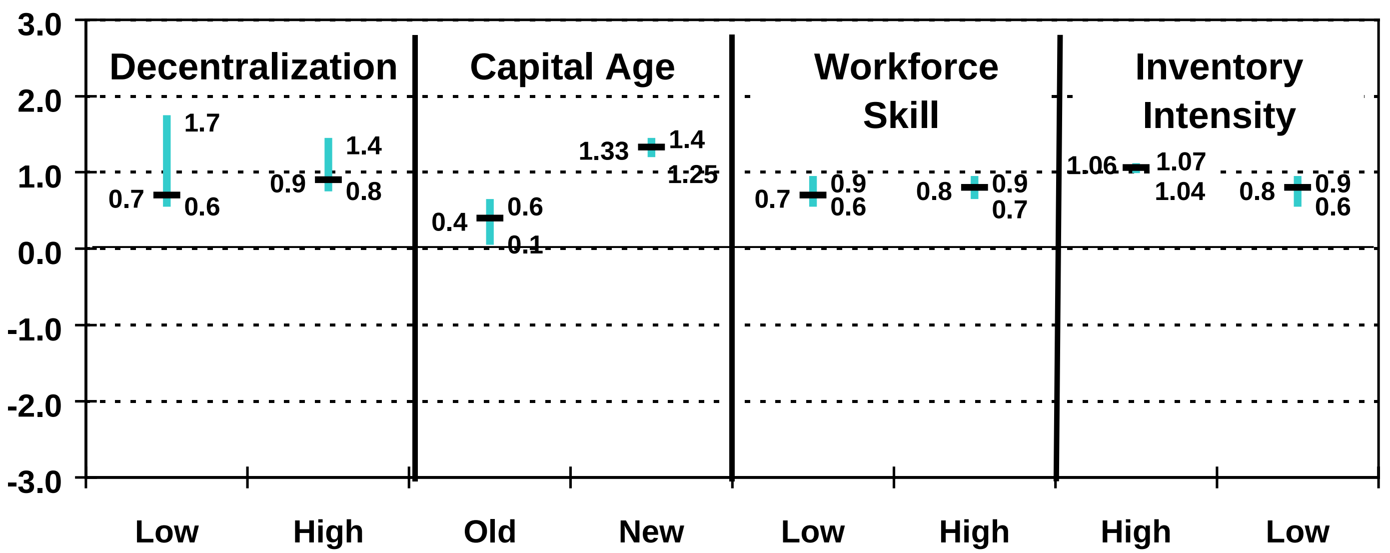


Figure 2: IT-Labor Substitution across sample splits (Medians and Quartiles Shown)



References

Allen, R. D. G. 1953. *Mathematical Analysis for Economists*. Macmillan and Co., London.

Anbil, R., E. Gelman, B. Patty, R. Tanga. 1991. Recent Advances in Crew-Pairing Optimization at American Airlines. *Interfaces* **21** 62-74.

Applegate, L., J. Cash, D. Q. Mills. 1988. Information Technology and Tomorrow's Manager. *Harvard Business Review* November-December 128-136.

Autor, D., L. F. Katz, A. Kreuger. 1997. Computing Inequality: Have Computers Changed the Labor Market? Mimeo, Harvard, Cambridge, Mass.

Barua, A., C. H. S. Lee, A. B. Whinston. 1996. The Calculus of Reengineering. *Information Systems Research* **7** 409-428.

Berman, E., J. Bound, Z. Griliches. 1994. Changes in the Demand for Skilled Labor within U.S. Manufacturing Industries. *Quarterly Journal of Economics* **109** 367-98.

Berndt, E. R. 1992. *The Practice of Econometrics: Classic and Contemporary*. Addison-Wesley Pub. Co., Reading, Mass.

Berndt, E. R., M. S. Khaled. 1979. Parametric Productivity Measurement and Choice among Flexible Functional Forms. *Journal of Political Economy* **87** 1220-45.

Berndt, E. R., C. J. Morrison. 1995. High-tech Capital Formation and Economic Performance in U.S. Manufacturing Industries: An Exploratory Analysis. *Journal of Econometrics* **65** 9-43.

Berndt, E. R., C. J. Morrison, L. S. Rosenblum. 1992. High-Tech Capital, Economic Performance and Labor Composition in U.S. Manufacturing Industries: An Exploratory Analysis. MIT Working Paper 3414EFA, Cambridge, Mass.

Berndt, E. R., D. O. Wood. 1975. Technology, Prices, and the Derived Demand for Energy. *Review of Economics & Statistics* **57** 259-68.

Bresnahan, T. 1997. Computerization and Wage Dispersion: An Analytic Reinterpretation. Mimeo. Stanford University, Stanford, CA.

Brynjolfsson, E. 1994. Information Technology and the 'New Managerial Work'. In *Organizational Learning and Experience Transfer*. J. Moe., ed. Norwegian Academy of Technological Sciences, Trondheim, Norway 27-101.

Brynjolfsson, E., T. W. Malone, V. Gurbaxani, A. Kambil. 1994. Does Information Technology Lead to Smaller Firms? *Management Science* **40** 1628-1644.

Brynjolfsson, E., L. Hitt. 1995. Information Technology as a Factor of Production: The Role of Differences Among Firms. *Economics of Innovation and New Technology* - Special Issue on Information Technology and Productivity Paradox **3** 183-200.

Brynjolfsson, E., L. Hitt. 1996. Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending. *Management Science* **42** 541-558.

Brynjolfsson, E., L. Hitt. 1996. The Customer Counts. *Information Week* September.

Brynjolfsson, E., L. Hitt. 1997. Computing Productivity: Are Computer Pulling Their Weight? Mimeo, MIT, Cambridge, Mass.

Brynjolfsson, E., H. Mendelson. 1993. Information Systems and the Organization of Modern Enterprise. *Journal of Organizational Computing* (December).

Brynjolfsson, E., A. Renshaw, M. Van Alstyne. 1997. The Matrix of Change. *Sloan Management Review* **38** 37-54.

Caves, D. W., L. R. Christensen. 1980. Global Properties of Flexible Functional Forms. *American Economic Review* **70** 422-32.

Christensen, L. R., D. W. Jorgenson, L. J. Lau. 1973. Transcendental Logarithmic Production Frontiers. *The Review of Economics and Statistics* **55** 28-45.

Clemons, E. K., S. P. Reddi, M. C. Row. 1993. The Impact of Information Technology on the Organization of Economic Activity: The "Move to the Middle" Hypothesis. *Journal of Management Information Systems* **10** 9-35.

Corder, R. 1997. Changing Human Resources to make Flexible Manufacturing Systems (FMS) Successful. *Journal of High Technology Management Research* **8** 263-275.

Council of Economic Advisors, 1998. "Economic Report of the President."

Davenport, T. H., J. E. Short. 1990. The New Industrial Engineering: Information Technology and Business Process Redesign. *Sloan Management Review* **31** 11-27

Dewan, S., C. Min. 1997. The Substitution of Information Technology for Other Factors of Production: A Firm Level Analysis. *Management Science* **43** 1660-16

Drucker, P. F. 1988. The Coming of the New Organization. *Harvard Business Review* January-February 45-53.

Fisher, M., J. H. Hammond, W. R. Obermeyer, A. Raman. 1994. Making Supply Meet Demand in an Uncertain World. *Harvard Business Review* May-June 83-93.

Galbraith, J. 1977. *Organizational Design*. Addison-Wesley Pub. Co., Reading, Mass.

Hall, B. H. 1990. The Manufacturing Sector Master File: 1959-1987, Documentation. NBER Working Paper 3366.

Hammer, M. 1990. Reengineering Work: Don't Automate, Obliterate. *Harvard Business Review* July-August 104-112.

Harvard Business School. 1988. Phillips 66: Controlling a Company Through Crisis. HBS Case 9-189-006.

Hayek, F. 1945. The Use of Knowledge in Society. *American Economic Review* **35**. Excerpt from L. Putterman and R. Krozner, eds. 1997. *The Economic Nature of the Firm*. Cambridge University Press, New York.

Hicks, J. 1970. Elasticity of Substitution Again; Substitutes and Complements. *Oxford Economic Papers* **22** 289-296.

Hitt, L. 1996. Information Technology and Firm Boundaries: Evidence from Panel Data. Mimeo, University of Pennsylvania, The Wharton School, Philadelphia, PA.

Hitt, L., E. Brynjolfsson. 1997. Information Technology and Internal Firm Organization: An Exploratory Analysis. *Journal of Management Information Systems* **14** 81-101.

Huselid, M. 1994. The Impact of Human Resource Management Practices on Turnover, Productivity, and Corporate Financial Performance. *Academy of Management Journal* **38** 635-672.

Ichniowski, C., T.A. Kochan, D. Levine, C. Olson, G. Strauss. 1996. What Works at Work: Overview and Assessment. *Industrial Relations* **35** 299-333.

Ichniowski, C., K. Shaw, G. Prennushi. 1997. The Effects of Human Resource Management Practices on Productivity. *American Economic Review* **87** 291-313.

Kreuger, A. 1993. How Computers Have Changed the Wage Structure: Evidence from Microdata, 1984-89. *Quarterly Journal of Economics* **108** 33-60.

Leavitt, H. J., T. L. Whisler. 1958. Management in the 1980s. *Harvard Business Review* (November-December).

Lichtenberg, F. R. 1995. The Output Contributions of Computer Equipment and Personal: A Firm-Level Analysis. *Journal of Economics of Innovation and New Technology* **3** 201-217.

Lucas, H. C. 1995. *The T-Form Organization*. Jossey Bass Publishers, San Francisco, CA.

Lucas, H. C. 1997. *Information Technology for Management (7th Edition).* McGraw Hill. New York

MacDuffie, J. P. 1995. Human Resource Bundles and Manufacturing Performance: Organizational Logic and Flexible Production Systems in the World Auto Industry. *Industrial and Labor Relations Review* **48** 197-221.

MacDuffie, J. P., K. Sethuraman, M. L. Fisher. 1996. Product Variety and Manufacturing Performance: Evidence from the International Automotive Assembly Plant Study. *Management Science* **42** 350-369.

Malone, T. W. 1997. Is 'Empowerment' just a Fad? Control, Decision-making, and Information Technology. *Sloan Management Review* **38** 23-35.

Malone, T. W., J. F. Rockart. 1991. Computers, Networks and the Corporation. *Scientific American* September 128-136.

Milgrom, P., J. Roberts. 1990. The Economics of Modern Manufacturing: Technology, Strategy, and Organization. *American Economic Review* **80** 511-528.

Osterman, P. 1994. How Common is Workplace Transformation and Who Adopts It? *Industrial and Labor Relations Review* **47** 173-188

Piore, M., C. Sabel. 1984. *The Second Industrial Divide*. Basic Books, New York.

Pollak, R. A., R. C. Sickles, T. J. Wales. 1984. The CES-Translog: Specification and Estimation of a New Cost Function. *Review of Economics and Statistics*. **66** 602-07.

SAP Annual Report. 1998.

Sarkis, J. 1997. An Empirical Analysis of Productivity and Complexity for Flexible Manufacturing Systems. *International Journal of Production Economics* **48** 39-48.

Simon, Herbert A. 1976. *Administrative Behavior (3rd Edition).* The Free Press, New York.

Smith, B. C., J. F. Leimkuhler, R. M. Darrow. 1992. Yield Management at American Airlines. *Interfaces* **22** 8-31.

Subramanian, R., R. P. Scheff, Jr., J. D. Quillinan, D. S. Wiper, R. E. Marsten. 1994. Coldstart: Fleet Assignment at Delta Air Lines. *Interfaces* **24** 104-120.

Varian H. R. 1992. *Microeconomic Analysis (3rd Edition).* Norton, New York.

Womack, James and Roos (1988). *The Machine that Changed the World*. Cambridge: MIT Press.

Zarembka, P. 1970. On the Empirical Relevance of the CES Production Function. *Review of Economics and Statistics* **52** 47-53.

Appendix A: Human Resource Practice Survey Questions

Decentralization is measured as the standardized sum of SMTEA, QUALC, XPACE, XMETH, SCNED, TRAIN, PROTE. This measure has a Cronbach's Alpha of .77, and all of these variables load highly on a single principal component. See Hitt and Brynjolfsson (1997) for further detail.

(SMTEA). Does your firm use "self-managing teams"?
____ (yes, no) [If no, skip to next question]

Would you say your firm uses self-managing teams very heavily, heavily, moderately or slightly?
___ Very heavily
___ Heavily
___ Moderately
___ Slightly

(QUALC). Does your firm use "employee involvement groups"?
____ (yes, no) [If no, skip to next question]

Would you say your firm uses employee involvement groups very heavily, heavily, moderately or slightly?
___ Very heavily
___ Heavily
___ Moderately
___ Slightly

Next I want to know about the arrangement between workers and managers in the conduct of the work.

	Exclusively Workers	Mostly Workers	Equally	Mostly Managers	Exclusively Managers
a. (XPACE) Who sets the pace of work?	☐	☐	☐	☐	☐
d. (XMETH) Who decides how the tasks should be accomplished?*	☐	☐	☐	☐	☐

* The variables METH and PACE were the original variables from survey one, coded 1-3 XMETH and XPACE are from survey 2 and 3 and were recoded onto the 3 point scale (1=1, 2=1.5, 3=2, 4=2.5, 5=3).

(TEAMB). Does your firm use team-building or group cohesion techniques?
____ (yes, no) [If no, skip to next question]

Would you say your firm uses these techniques very heavily, heavily, moderately or slightly?

___ Very heavily
___ Heavily
___ Moderately
___ Slightly

How important are the following criteria when conducting pre-employment screens for new production workers?

	Extremely	Very	Somewhat	Not too	Not at all
a. (SCNED) Would you say educational background is extremely important, very important, somewhat important, not too important or not at all important?	☐	☐	☐	☐	☐

(TRAIN). What percentage of production workers received any work-related training off-the-job during the last 12 months? *("Off-the-job" training includes classroom training, or courses or seminars apart from regular work activities.)*
_____ %

Now I would like to ask about the promotion of workers. How important are the following factors when promoting production workers?

	Extremely	Very	Somewhat	Not too	Not at all
a. (PROTE) Would you say teamwork is extremely important, very important, somewhat important, not too important or not at all important?	☐	☐	☐	☐	☐
b. (PROSK) How important is skill acquisition?	☐	☐	☐	☐	☐