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INFORMATION TECHNOLOGY, WORKPLACE ORGANIZATION, AND THE DEMAND FOR SKILLED LABOR: FIRM-LEVEL EVIDENCE

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ABSTRACT

Recently, the relative demand for skilled labor has increased dramatically. We investigate one of the causes, skill-biased technical change. Advances in information technology (IT) are among the most powerful forces bearing on the economy. Employers who use IT often make complementary innovations in their organizations and in the services they offer. Our hypothesis is that these co-inventions by IT users change the mix of skills that employers demand. Specifically, we test the hypothesis that it is a cluster of complementary changes involving IT, workplace organization and services that is the key skill-biased technical change.

We examine new firm-level data linking several indicators of IT use, workplace organization, and the demand for skilled labor. In both a short-run factor demand framework and a production function framework, we find evidence for complementarity. IT use is complementary to a new workplace organization which includes broader job responsibilities for line workers, more decentralized decision-making, and more self-managing teams. In turn, both IT and that new organization are complements with worker skill, measured in a variety of ways. Further, the managers in our survey believe that IT increases skill requirements and autonomy among workers in their firms. Taken together, the results highlight the roles of both IT and IT-enabled organizational change as important components of the skill-biased technical change.

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1 Introduction

1.1 Technology, wage inequality and the demand for skilled labor

Over the past two decades, wage inequality has grown significantly in the United States. The total effect has been large, as the gap between wages at the 75th percentile of the distribution and the 25th has increased by nearly 50 percentage points.[1] The total effect has also been widespread, shifting relative wages in the top, middle, and bottom of the income distribution. The main cause of the growth in inequality appears to be a shift in the demand for workers of different kinds. Demand is growing for workers with exceptional talent, training, autonomy, and management ability much faster than for workers in low and middle-wage occupations.

Parts of this shift in labor demand are explained by such broader economic patterns as globalization, sectoral shifts in employment and changes in labor market institutions. Yet these forces appear too small to explain the breadth and depth of the shift, leaving a large residual shift (Krugman and Lawrence, 1993). Economists have concluded that this residual must reflect a "skill-biased technical change" in the way goods and services are produced in the economy (Griliches, 1969; Berndt, Morrison and Rosenblum, 1992; Berman, Bound and Griliches, 1994). The nature of this technical change are still not well-understood, but its size, breadth, and timing have led many observers to link it to the largest and most widespread technical change of the current era, information technology (see, e.g., Autor, Katz, and Krueger, 1997 and references therein).

In this paper, we examine the firm-level evidence for a specific theory of how information technology (IT) could cause skill-biased technical change. In particular, we argue that the effects of IT on labor demand involve far more than simple automation and substitution. Instead, we highlight the central role of IT-enabled organizational change in

[1] Murphy and Welch (1993) show percentiles of the wage distribution of prime-age males: the interquartile range has increased from about 1.75 to 1 to about 2.25 to 1. More extreme percentiles have moved even farther from the median, so that the entire distribution of wages is widening over time.

a cluster of complementary and mutually reinforcing innovations that X change work fundamentally.

Employers adopt IT-based production processes to improve service quality or increase efficiencies and thereby increase profits. In either case, effective use of IT involves changes to organization. Examination of the form of the organizational changes suggests a theory of why IT-based technical change is skill-biased (Bresnahan (1997)). First in service-producing sectors like finance, then in the service parts of goods-producing industries, firms have found ways to take advantage of new production processes that use IT intensively (Barras (1990)). They have found it very difficult to profit by just replacing other factors with computers and telecommunications gear while making the same products. Often, the benefit of the new production process is new services or improved service quality. Further, the new production process involves global changes to the organization.[2] These often involve replacing low-skill human workers (automation), while passing on to humans an increased variety of tasks related to the higher level of service. A similar pattern holds for attempts to achieve IT-based efficiencies in production. Only with organizational change, typically of a kind that involves complementarity with high skill as well as substitutability for low skill human work, do employers get the benefit they seek from IT.

These observations lead us to an analysis based on a cluster of complementarities that we see as at the heart of recent changes in labor demand. Intensive use of IT, higher service levels for customers, and organizational change all go together, and together call for higher-skilled labor. These form a mutually reinforcing cluster of inventions for employers. Critically, the organizational changes associated with IT-based service improvements are skill-using. The key skill-biased technical change of the present can thus be seen to consist not only of IT, but of the complete cluster of associated complements. The "technical" side of this cluster is the large, ongoing declines in IT prices and large, ongoing improvements in IT performance. It is tightly linked to labor

[2] Among the first to predict this effect were Leavitt, and Whisler (1958). There are by now many papers which illustrate the role of IT-enabled organizational change at varying levels of detail, notably Attewell and Rule (1984), Crowston and Malone (1988), Malone, Yates and Benjamin (1987), Milgrom and Roberts (1990), Brynjolfsson, Renshaw and van Alstyne (1997), Bresnahan and Greenstein (1997), and

demand through its organizational side. Investments in the complete cluster, including the dollars, time, and effort associated with the organizational change are likely to be substantially larger than the IT investments themselves, even if they are more difficult to quantify.

1.2 Aggregate data suggest IT is behind the labor demand shifts

Broad-based studies of the labor market are consistent with the hypothesis of an IT-based demand shift.

An important body of research looks at wage determination at the level of individual workers or jobs. A wide variety of studies have examined individual worker wage equations (surveyed in Gottschalk, 1997). Based on large data sets, such as the Current Population Survey, these studies predict wages with both observables – education and experience – and unobservables – the residual in the wage equation. The observables are interpreted as proxies for skills. Changes in their coefficients over time are interpreted as changes in the prices of those skills. When the distribution of the residual spreads out, it is interpreted as an increase in the price of an unobserved skill. The important results from these studies are that the relative demand for more highly educated workers is rising (probably related to general cognitive skill), that the relative demand for more experienced workers is rising (likely specific knowledge or managerial/people skills) and that the relative demand for "residual" highly skilled workers (skills not captured by education or experience) is rising as well.

A related literature classifies occupations by skills and examines the wages and employment changes for work thus classified (see, e.g., Howell and Wolff, 1991). These studies also find considerable support for the view that relative demand is shifting toward cognitive and interpersonal interaction skills.

The difficulty with both these bodies of empirical inquiry is the same. While they can reveal the effects of changes in labor demand, they do not examine the demanding unit. They look at the demanded unit – the worker or the job. Accordingly, their ability to examine alternative stories of demand is quite limited.

Brynjolfsson and Hitt (1997). It has also been an important theme in the management literature (Davenport and Short (1990) and Hammer, (1990)).

Another body of studies gets closer to the demanding unit by looking at industries. Here there is also a very clear finding. The IT-intensive industries, have seen the demand shift earlier (Wolff (1996)) and to a larger extent (Autor, Katz and Krueger (1997)) than other industries. This finding appears to be robust to how computer-intensity is measured, as looking at investments in all IT capital and looking at the fraction of workers in an industry that use a computer or terminal yield comparable results. The finding is particularly strong in services.

An industry may be simply too wide a unit to capture the relevant flows of causation. Industries contain variety across firms in IT-use strategies. Industries contain variety in service and product strategies. Industries contain variety in organizations of work. Our study, focussing on the firm level behavior, is pointed more closely at the relevant unit of demand.

1.3 Outline of the paper

In the next Section, we use a simple production function framework to explain our view of the relevant complementarities. We then derive the implications for labor demand in Section Three and summarize the data we use to test our theory in Section Four. Section Five presents our findings regarding the correlations among the variables, firm productivity and managers' opinions about the effects of IT. In Section Six we derive some implications and Section Seven we summarize our conclusions.

2 What does "Computerization" mean? The Case of White-collar Bureaucracies

The key to our argument is that computerizing a firm involves far more than installing computers. Typically, success requires that the firm's work organization and the nature of it's services and products must also be reinvented in myriad large and small ways. As a result, the types of workers employed and the skills of those workers are likely to change.

In this section, we take up the implementation of computer business systems for labor demand in white-collar bureaucracies.[3] There are two stages. First, we summarize

[3] Many of the same implications are present in blue-collar contexts (see for instance the case study of "Macromed" in Brynjolfsson, Renshaw and van Alstyne, 1997), but for brevity we do not

our overall view of the complementarities. This revolves around the graphical presentation in Figure 1. We then discuss the specifics of the relationship between IT-enabled organizational change and the shift in labor demand patterns.

Computer business systems change white-collar work. One way they change it is by organizing, routinizing and regularizing tasks that people- and paper-based systems did more intuitively but more haphazardly. They also change work by changing the nature of the firm's output, especially in the service sectors, and in the white-collar activities of the goods sectors. Computer-based production leads to higher levels of service or even whole new services and products. The labor-demand impact comes at the firm level, as computer business systems form the modern production process for many service industries (and for the service functions of other industries.) As computers have grown cheaper, and especially as computer networking has improved, computer-based production has spread more and more widely through white-collar work.

2.1 IT, Organizational Innovations and Improved Services are Mutual Complements

An emerging view of the way IT comes to be used in companies is represented in the bottom half of Figure 1. This view, which has considerable support in earlier work,[4] emphasizes complementarity among three distinct kinds of technical change. The three complements are:

- Cheaper, more powerful IT Capital
- Organizational Change
- New Products, Services or Quality

The theory we will test is that the cluster of three complements at the bottom of Figure 1 represents, together, a form of skill-biased technical change. Implementing all three of these forms of technical change together transforms companies and leads to substantial changes in labor demand by type. We need not make any assumption that one

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emphasize them. A very substantial portion of work in modern economies is in purely white-collar industries, such as service industries, or in the white-collar functions of goods-producing industries. We focus particular attention on the parts of bureaucracies that are associated with transactions. These are associated not only with a great deal of the IT-related technical change of the past, but also, as electronic commerce grows more important, with the IT-related technical progress of the future.

of these three uniquely causes the other, only that they tend systematically to go together. Since all three involve substantial amounts of invention, the complementarity arises in the long run. Taken together, the three forms of technical change are the cluster of driver technologies for labor demand we study.

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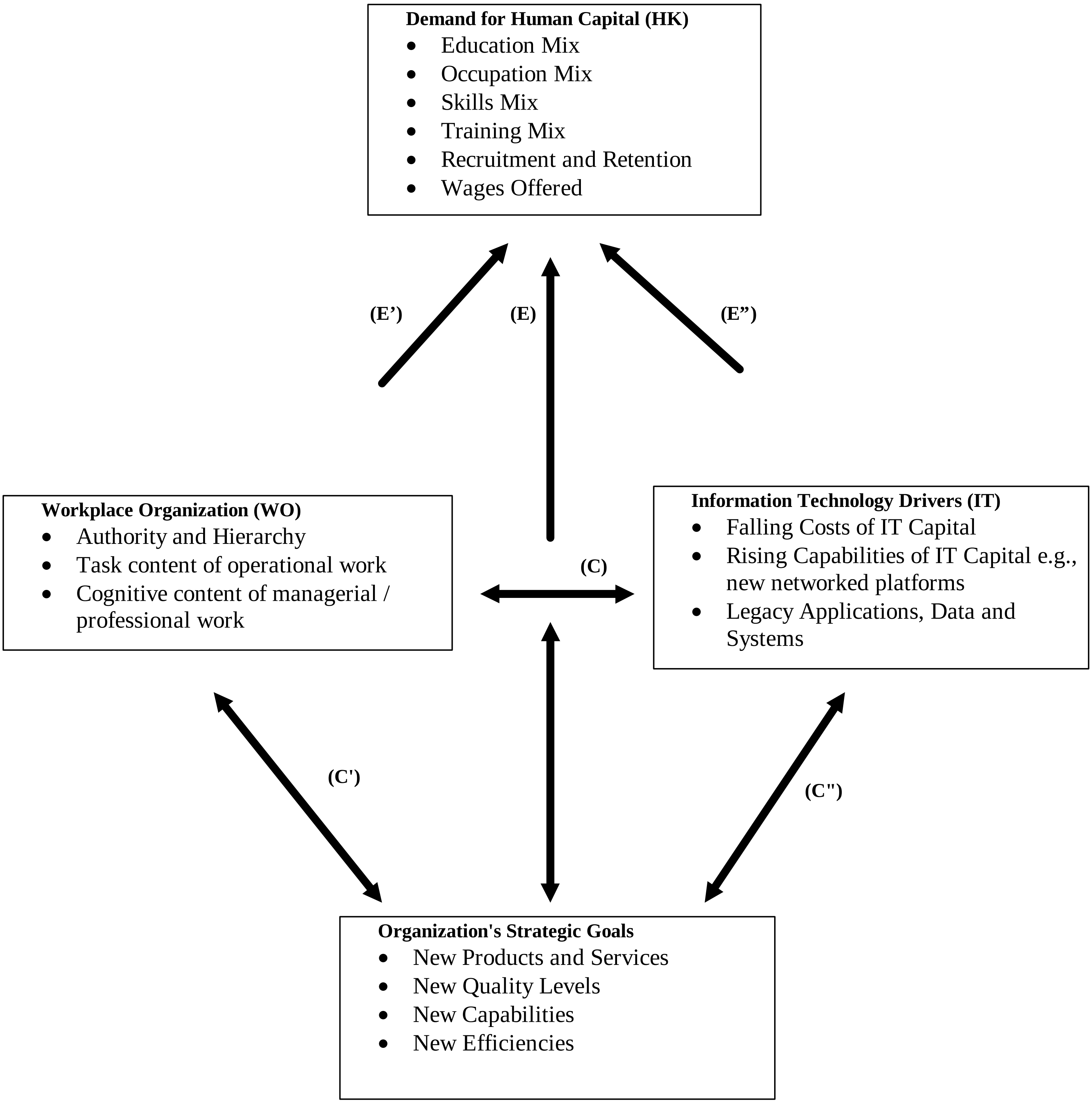
[4] See for example Applegate, Cash and Mills (1988), Barras (1990), Davenport and Short (1990), Levy and Murnane (1996), Malone and Rockart (1991), Milgrom and Roberts (1990), Orlikowski (1992), Scott Morton (1991), Simon (1973), Zuboff (1988).

Figure 1: Causal Flows in Our Framework



2.2 A Production Function Framework

The next step moves us toward specificity by having a simple framework for the inputs and outputs of white-collar work. We show our framework in a descriptive way in Figure 2 and in a more analytical way in Figure 3.

Figure 2: The Production Function Framework

Detailed Inputs		**Detailed Production Process**		**Detailed Outputs**
Labor of several types		Tasks for each input		Services
IT capital of several types	=>	Job responsibilities & computer programs	=>	Transactions
Other capital goods of several types		Organizational structure of inputs, hierarchy, etc.		Control

The view we take of the production function is one that has a detailed presentation of inputs, processes, and outputs. Labor and capital of several different types are the inputs. This gives us the opportunity to represent our fundamental long-run driver, declines in the price of IT capital goods. It also gives us the opportunity to represent our fundamental dependent variable, demand for labor of different skill levels. The detailed production process and detailed outputs play a different role. They permit us to state a specific theory about the mechanisms by which changes in the price of IT affect the demand for labor in the intermediate run. They also offer some further dependent variables tied to the mechanisms of the theory.

The production of detailed outputs is particularly important here, and illustrates why we take a detailed view of the production process. A white collar bureaucracy's outputs do not only consist of what the bureaucracy literally does – the services it makes for customers or the transactions it processes with customers or suppliers. Above and beyond the simple completion of its task, a bureaucracy produces managerial control of the task.

This may be illustrated by simple examples. Consider a department with responsibility for accounts receivable. What does it produce? It produces, in a literal sense, transactions in which the firm collects money and a record of those collections. If we think literally about the "service quality" associated with those, it suggests collecting most of the money owed the firm, not annoying customer/debtors too much, and so on. A broader view includes the firms' control of its receivables and of the collection process in the output. Can the firm identify problem accounts for special attention? In allocating new trade credit associated with new sales, can the firm discriminate between rapid payers and slow ones? Can it do this unobtrusively and quickly?

Both the narrow and the broad view of output suggest a changed role with computerization. Better record keeping clearly makes it possible to collect each bill once and only once. Combined with some changes in policies and procedures, it also makes it possible for salespeople to know the credit status of an account while in the process of making a sale.

More generally, these examples reveal two things about the IT-based production process from a very operational perspective. First, as IT has grown cheaper and more powerful, the number and kind of white-collar processes it can automate in this way has grown. More and more interactions in the business world are undertaken with this kind of computer support. That means more and more substitution out of certain kinds of human effort. Computers have been especially successful in routine, repetitive tasks, which are typically those that have not been highly rewarded historically. Second, computerizing tasks makes it much easier to accumulate data, both intentionally and as a by-product of other tasks.[5] A firm can decide to retain a systematic record of all its interactions with a customer, or all of a given employee's interactions with customers, for example. This is a much lower-cost decision given that the interactions are mediated through IT. As more and more interactions are so mediated, the complexity of record keeping and record analysis can grow. This offers opportunities for the new uses of human intelligence.

[5] The introduction of bar code scanners to supermarkets might seem to be primarily a way to save labor by cashiers. However, this benefit is vastly outweighed by the benefit of analyzing scanner-derived product data to improve inventory control, supply-chain management, marketing and promotion programs, and pricing strategies.

Figure 3: Short Run Production Function Notation

Detailed Inputs		Detailed Production Process		Detailed Outputs
$L_1 \ldots L_M$ $K_1 \ldots K_M$	=>	Indexed by T, S	=>	X Q

Moving to Figure 3, we show the way we will represent the detailed outputs and inputs. L and K are vectors of labor and capital types, respectively. X measures the quantity of various services or transactions, and Q represents the service level or degree of control over those transactions that the bureaucracy offers. T and S index the technologies used in production and the organizational structure of production, respectively. These are the things usually left in the black box.

The link to factor demand is via a short run production function:

$$\mathbf{0 = F\,(L_1 \ldots L_M\,,\, K_1 \ldots K_M,\; X;\, Q,\, T,\, S)}$$

That is, the detailed labor and capital requirements are determined by the level of output, output qualities, and the technology and organizational structure used in the firm. This is a short-run production function because it conditions on the organizational variables fixed by the firm in the intermediate run.

Our analysis will focus on the short run and the intermediate run. The short run has Q, T, and S fixed, and we look at the relationship between the capital (IT) and labor factors of production. In the intermediate run, Q, T, and S can be improved by the firm, perhaps because of the complementarities associated with (C'), (C"), (C) and so on. The relationship between the two runs and Figure 1 is as follows. In the short run, Q, T, and S are fixed, and only flow of causation (E") is available to change labor demand. In the intermediate run, organizational structure and service are flexible, so that flows of causation (E) and (E') also come into play. We believe that both the short and intermediate run causal flows can be seen in our data. We are less certain that they can be distinguished.

It is worth noting at this stage that this framework is designed to look at the individual firm. Further organizational changes associated with changes in the boundary of the firm will not be fully captured in firm data, nor will they enter our framework. We conjecture that we are, as a result, leaving out one of the important flows of causation from IT-based organizational change to labor demand. We will miss, both theoretically and empirically, much of the impact of the creation of new specialty firms employing highly paid workers, for example.

3 Implications of the Theory for Labor Demand

3.1 Limited substitution

Computer business systems involve the regularization and routinization of white-collar tasks. Simple, repetitive tasks are far more amenable to regularization and routinization than more complex and idiosyncratic ones. The result has been the systematic substitution of computer decisionmaking for human decisionmaking in clerical (and similar bureaucratic) work. Decisions that were once reached by humans in a paper- and people-based system are now reached by software. Advances in artificial intelligence notwithstanding, the scope of this substitution has been limited. Simple decisions, closely related to individual transactions or other operational actions, have been most amenable to computerization. More complex and cognitively demanding work, such as that of managers and professionals, has proved remarkably difficult to automate with computers. Similarly, tasks that require judgment, creativity and frequent exceptions are much more difficult to computerize than well-defined and repetitive tasks. Computer automation of white-collar work has been correspondingly limited in its scope, affecting demand for clerks and expediters far more than for managers and professionals.

This limited substitution is related to all three of the causal arrows (E), (E'), (E'') in Figure 1. First, but probably least important empirically, is the narrow flow of causation from the use of IT capital alone to substitution out of low-cognitive skill labor; this is (E''). In the short run, holding Q and S constant, it is sometimes possible to literally replace people with IT, holding other aspects of the organizational system constant. A telephone-switching computer replaces a telephone operator in a variety of tasks, an automatic teller machine replaces a bank teller, and documents once organized and filed by clerks are instead handled entirely by machine. Yet these examples – and even they are imperfect, involving considerable change in Q, and S as well as T – are rare.

Far more important is substitution of computer for human decisionmaking in the intermediate run, with corresponding changes in T, Q, and S. This reflects that fact that job design and the allocation of tasks to workers combine tasks which use similar information sets, or which it is efficient to monitor together, which have similar skill requirements, or which should be performed geographically close together (Holmstrom and Milgrom (1991), Jensen and Meckling (1992), Williamson (1979)). Yet, computers have very different strengths and weaknesses than humans. As a rule, computerization significantly changes at least one, and more often all, of these factors influencing job design. As a result, successful computerization also requires a rethinking of how work is organized and the types of workers required.

This can perhaps be most simply seen in a homey example from Accounts Receivable (AR). Almost everyone has heard of how early applications lacked the commonsense of human clerks, for example sending bills for $0.00. A computer needs to be told not to send a bill for $0.00, whereas (many) clerks could be relied upon to do this without explicit instruction. After a while, the software system in an AR application improves and the system stops making these silly mistakes. Or the company adopts an organizational change, such as a human clerk who can override the system when it is obviously doing something silly. Improvements in T – better software systems – made the computer a better substitute for a clerk. Improvements in S – such as using the fact that the clerk's actions are now well recorded to permit autonomy, or using the computer's memory to permit any of a wide variety of clerks to deal with a particular account in a teamwork fashion – make the clerk plus the computer an improved production process. These improved rules draw on the very distinct capabilities of IT and humans. They can only effect labor demand with some invention by the firm. The invention is as much of improved work organization as it is of improved software.

This tendency for improvements in T and S to offer opportunities to substitute out of L into K is quite general. There are some common-sense rules in any bureaucracy.

Where common sense can be reduced to rules, or where the business can get by with a little less common sense, or where common sense can be reorganized into a human-override, IT systems can be made to substitute for simple human decisionmaking. It is especially true where S changes.

There are, however, strict limits to this substitution, for all its power. As a result, some types of work are affected far more than others.

3.2 Increased demand for cognitive skills

The IT-related cluster of innovations is not merely a substitute for low cognitive skill labor. It is also a complement for high cognitive skill labor. These two effects of computerization combine to change the demand for skilled labor. In this subsection, we look at the more complex causal relationship between the IT-related cluster and high cognitive skill workers such as managers and professionals.

3.2.1 Direct Causal Flows

There is an important causal flow directly from IT capital to use of very skilled technical workers of an (E") form. Computer departments themselves employ highly skilled people. So, to, does the computer services industry. (This industry is an extension of company computer departments. It offers custom programming, consulting, and systems integration to user companies.) Finally, there is a related effect on demand in the computer hardware, software, and networking industries themselves. In the US, though not to any very large extent in other countries, this represents a substantial demand for cognitive skill. Aggregating all these flows will not, however, amount to a very large fraction of employment (Bresnahan, 1997). We need to look elsewhere for a substantial complementarity between the IT-based cluster and high cognitive skill.

Another direct causal flow of the (E") variety has been widely discussed but is likely to be of limited importance. This is the direct use of personal computers (PCs) by individual workers in organizations. By far the largest single use of PCs is for word processing.[6] Anecdotes about excessive font-futzing and lost data notwithstanding, typists and secretaries have clearly become much more productive as a result. However,

[6] The statements about the relative importance of various PC applications are based on data from Computer Intelligence Infocorp.

this is an implausible source of wage dispersion. Meanwhile, managers and professionals who do their own typing may also become somewhat more productive with PCs, but this is also an unlikely explanation for their higher relative wages. Similar arguments apply to the other dominant PC applications, spreadsheets and graphics. However, a minority of more specialized applications, such as PC-based computer aided design and project management, are more promising candidates for skill complementarity. The growing organizational uses of PCs, which can affect the wages of even those managers who do not literally use computers, are likely to be especially important (see further discussion in Bresnahan, 1997).

3.2.2 Causal Flows Through Organizational Change

Many effective uses of computers make use of IT's comparative advantage in doing simple tasks quickly, and in remembering a large volume of simple information and recalling it rapidly. Many times, these features of computers are most effective when combined with human intelligence. For example, a typical "analytical" application consists almost entirely of complex data storage and recall. Rapid, detailed memory by computers is often a complement for human judgement in decisionmaking. In our accounts-receivable example, the computer may quickly report a summary of a particular customer's payment history. That is an "analytical" application. As a result, firms like Capital One (a major credit card issuer) are hiring more MBAs and even Ph.D.s to help them analyze customer data that they collect so easily with IT. Human judgement might have the final say in whether a particular account's value to the firm warrants extending trade credit in particular circumstances or whether a new type of product or service is likely to be successful with a particular customer segment.

A related kind of effective use of the computer's detail and completeness turns the "analytical" lens on workers and departments within the firm. Detailed reports on the success – measured by anything the computer system knows systematically – of individual workers or departments are a kind of management tool that has grown cheaper with the falling costs of computerization. In Figure 1, this kind of increased demand for highly skilled labor shows up as an (E) flow, that is, one that involves changes both in computerization and in organization.

This complementarity between machine and human capabilities leads to a wide variety of organizational structures, but some specific ones are worth mentioning here. One is the information-enabled decentralized worker. In the most extreme form, this involves use of a worker who is supported by analytical applications that let her know everything she needs to know to accomplish her task. She is in turn monitored by a computer analytical application that permits her superiors to monitor her performance quickly and efficiently. Less extreme examples vary in a number of ways. They might have the human unit that is supported and monitored be a team rather than an individual worker. They might use only one of the support/monitoring flows of information.

Note that this tendency toward computer-based reorganization calls for several very different changes in worker capabilities. The first is cognitive. Individual workers or teams supported by analytical applications means must be able to interpret the information that is presented. Often, this involves bridging from the quantitative data provided by computers to complex decisions involving many factors. In a wide variety of applications, computers have made information vastly cheaper and more abundant. This increases the demand for humans who can process information processing in ways that machines cannot. Indeed, it creates an information-overload bottleneck. Simon (1973) noted this not long after the first widespread use of computers in business that "The scarce resource is not information, it is the processing capacity to attend to information. Attention is the chief bottleneck in organizational activity, and the bottleneck becomes narrower and narrower as we move to the tops of organizations." Thus, in addition to a general increase demand for human cognitive skills, computerization can lead to attempts to bypass the managerial bottleneck via new organizational forms which favor increased lateral communication and coordination.

A second set of human capabilities associated with this kind of organizational change has to do with autonomy more than with any specific cognitive skill. Monitoring technologies in general are useful for moving responsibility and authority. The monitoring technology associated with computer-based work appears to be systematically related to incentives, at least long run incentives, which are more closely tied to measurable performance. Not all workers come with equal tolerance for or capability to respond to these kinds of incentives. The change in the mode of supervision calls for changed talents.

A third set of human capabilities associated with this kind of organizational change involves the skills associated with dealing with customers and suppliers, influencing teammates and colleagues and inspiring and coaching subordinates. More generally, they involve providing the people skills which computers lack.

Additional complementarities of the (E) form, i.e., involving the three-way complementarity with organization, IT, and product change, arise from inventive dynamics of computer-based organizations. As we emphasized above, effective use of computer systems involves a great deal of invention by the using firms. It is a complex activity to discover and implement ways to gain from computers' capabilities. As computers have become more powerful, more flexible and more user-friendly, the largest and growing fraction of this inventive activity occurs outside of the programmers' job function. It is now the duty of those who use computers, directly and indirectly, in large ways and in small ways. In particular, this puts pressure on managers' and professionals' cognitive capabilities.

Adding more complexity, the most computer-intensive businesses typically use computers for improved customer service and as the basis for new and improved services. Invention of the new products those processes will deliver and of the human side of the delivery mechanism are very difficult cognitive tasks. They call for managers who can think of ways to take advantage of the new production processes offered by computing. This calls for new cognitive skills, having a deep understanding of one's own organization and one's customers' needs.[7] This raises the demand for high levels of cognitive skills in managers and professionals.

Some of these new demands on highly skilled workers can call for a great deal of human capability. It can be quite difficult to think about one's customers, for example, both through the lens of knowing them and the more analytical lens of seeing their

[7] Bartel and Lichtenberg (1987) suggest that high levels of cognitive skills may be particularly important in creating and adapting to change, notably in implementing new technology. The managerial side of computer-based production processes is an excellent example of this story. The constant improvements in computer technology mean that organizations that use IT intensely have this demand for high levels of cognitive skill on a standing basis, not just for a single transition.

behavior systematically in databases. Once the firm knows new and interesting things about its customers it must invent new ways to interact with them.

As more and more of business is mediated through computers, there are more and more opportunities for managers and professionals to undertake two activities. The first is research-like, combining IT-based quantitative information about customers or employees with deep knowledge of the business. The second is designing organizations, products, and so on, taking advantage of the new research findings. This, too, combines hard quantitative skills with deep business knowledge. To the extent that the new organization or product will be enabled by computer, the firm is specifying a new computer "program". Even those managerial and professional workers who never touch computers have their work transformed in this way, calling for more and more complex bodies of skill and knowledge as well as new organizational structures. Thoughtful designers of business information systems recognize the information overload bottleneck: "While we've seen a great revolution in bandwidth and computing power, unfortunately the input/output capability of human beings hasn't changed much over the last decade".[8]

3.3 The net impact of IT and IT-enabled organizational change

In computerized work environments, high levels of human information processing skills should be getting more valuable. In part, this reflects the potential of present-day computers to substitute more effectively for routine information processing tasks than for complex or ill-structured cognitive tasks. It also reflects a potential complementarity between some of the strengths of computers -- storing, communicating and executing instructions on a flood of data -- and many types of human judgement and decision-making. As Simon (1971) has noted "What information consumes is rather obvious: it consumes the attention of its recipients." In an information age, the scarce resource is human information processing.

One implications of this theory is that computerized firms will seek to address the increased relative demand for high cognitive skill labor by hiring more skilled and educated workers and by investing more heavily in training for existing workers. Another implication is that the information overload bottleneck is likely to be especially

[8] Robert Walker, CIO of Hewlett Packard, quoted in Mendelson and Pillai (1998).

severe higher up in the hierarchy. Human capital should be especially at a premium here. But firms will also seek non-hierarchical forms of organizing to bypass the bottleneck (e.g. "self-managing teams"). As a result, computerized firms should make greater use of self-managing teams and decentralized decision-making. Furthermore, in these firms, employees with "team" skills, and "autonomy" skills should become more valuable.

To summarize the implications of our theory for labor demand, information technology impacts the optimal organization of work, and impacts the demand for skills both directly and through changes in workplace organization.

4 Data Description

The data set used for our analyses is a cross sectional survey of organizational practices and labor force characteristics conducted in 1995 and 1996 matched to a panel detailing IT capital levels and mix over the 1987-1994 time period. For some analyses, we will also use data on other inputs and outputs, including non-IT capital, total employment, sales, and value-added. Data cover approximately four hundred large US firms. Approximately 55% of the sample are from the manufacturing, mining, or construction sectors and 45% are in services. More detail on the survey can be found in Brynjolfsson and Hitt (1997), and Bresnahan, Brynjolfsson and Hitt (1998).

4.1 Measures of key variables

In our empirical work, we useda simplified and streamlined version of Figure 1.

4.1.1 Human Capital

Our richest set of measures falls in the upper, human capital demand, box. We measure human capital (HK) in several direct ways: via the manager's assessment of workforce skill, the educational composition of the firm's workforce or the percentage of employees who are professionals, managers, clerical, etc. We also construct a broader measure of information work based on the percentage of all employees who are managerial, professional or clerical -- precise definitions of all constructed variables are in Table 3. Our interpretation is that these are alternative measures of the same broad concept -- a tendency at the firm level to use, or to attempt to use, more highly skilled workers.

While we observe those human capital measures only once in cross section, we also have a measure of the firm's policies toward human capital investment. HKI is defined as a mean zero, standard deviation one variable that is created from the percent of workers receiving training, the extent to which the firm screens for education in hiring and the firms' use of cross-training (definition, Table 3). This variable is more dynamic: it shows where human capital levels are changing whereas others reveal where they are high.

All these data were gathered via a survey administered to senior human resource managers or their designees. The survey based on questions from prior surveys on workplace organization and human resource practices (Ichniowski, Shaw and Prennushi, 1994; Osterman, 1994). In particular, 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") and focused on the organizational practices at the most typical establishment.[9] A total of 416 firms provided at least some data for the study. Descriptive statistics are in Table 1.

4.1.2 Workplace Organization

On the left of Figure 1 lies the concept of workplace organization. Workplace organization is notoriously difficult to measure and the changes in organizational structure that are complementary to IT capital might be particularly so. Gathering new data on workplace organization and linking these variables to IT capital at the firm level is one of the advances that permits this study, and the earlier ones by Brynjolfsson and Hitt.

In the broad and general sense, it is well established that organizational change and information technology are complements. However, only a subset of the relevant

[9] Because we are especially interested in firm-level effects, one difficulty of our sampling approach is that the practices reported by the respondent may not be representative of the work practices across the entire firm. To address this issue, the revised instrument contained questions about how representative production workers were in terms of total employment and the uniformity of work practices for this category of workers. For the average firm in the second survey subsample, production workers account for about two thirds of total employment and organizational practices are found to be fairly uniform: 65% of respondents said that all production workers have the same work practices. Furthermore, 82% reported that at least 80% of workers had the same work practices.

organizational changes is captured in our survey and used in our empirical work.[10] We focus on one particular type of organizational change that has been found to be important in earlier work by Brynjolfsson and Hitt (1997). Our variable WO is defined as a mean zero, standard deviation one variable reflecting the several distinct measures of workplace organization greater use of teams, greater delegation of a variety of decision rights to line workers, and activities that support the use of teams such as team building. (definition, Table 3.)[11] These variables have a clear interpretation as measures of decentralization. Our concept of workplace organization is narrow and specific.

Our data on organizational characteristics were gathered via the same survey used for our human capital data. Since these data are based on a snapshot at the end of the sample period, we do not know whether each firm had the same organizational characteristics throughout the sample period and in contrast to the human capital data, we do not have information on the levels of "investment" firms were making in organizational change. The reasonable interpretation based on aggregate data, however, is that many of the firms have only recently adopted these practices.[12] In a measurement sense, our measure of WO (a level at the end of the sample period), can also be interpreted as ΔWO (the amount of organizational change in the organization during the sample period).

4.1.3 Information Technology

At the right of Figure 1 is the concept of IT drivers. Our IT measures are stocks of computer hardware at the firm level and also stocks of specific types of hardware (e.g.

[10] For instance, we do not have any data on changes in outsourcing which might plausibly change the skill mix of remaining employees. Nor do we attempt to catalog and measure all the types of internal reorganization that might occur. Omitting these other forms of organizational change probably leads us to understate the role of organizational factors.

[11] This choice of measures reflects the first principal component of a factor analysis of responses to the organizational practices survey. Interestingly, Osterman (1994) reports that a similar set of team-oriented practices loaded on the first principal component in his survey of 694 establishments.

[12] The practices we use to define WO are very similar to the ones that , according to Ichniowski et al (1996), "have become increasingly common among U.S. businesses in recent years". In fact, Osterman (1994) asked about a similar cluster of work practices in a survey of 694 managers and found that 49.1% of the establishments in his sample reported introducing "teams" in the five years prior to his survey year of 1992. He also reports that 38% introduced job rotation practices, 71% TQM programs and 67.9% problem solving groups in the years between 1987 and 1992, each of which also reflects increased decision-making by line workers.

PCs).[13] Empirically, we view them largely as alternative measures of the same concept. A distinction among the types of computers between those suitable for organizational computing (mainframe and minicomputers) and those for personal computing (PCs) sharpens this somewhat. In the period of our data, however, PCs could be an indicator either of a tendency to personal computing or of new-architecture organizational computing. Thus the sharper interpretation is ambiguous and most of our interpretation is the broad one that some firms are more IT intensive than others.

The measures of IT use were derived from the Computer Intelligence Infocorp installation database that details IT hardware spending by site for companies in the Fortune 1000 (approximately 25,000 sites are aggregated to form the measures for the set of companies that represent the total population in any given year). This database provides details on the ownership for specific pieces of IT equipment and related products. These data include variables capturing the total capital stock of IT (central processors, PCs, and peripherals) as well as measures of computing capacity of central processors in millions of instructions per second (MIPS) and the number of PCs. The IT data do not include all types of information processing or communication equipment and are likely to miss a portion of computer equipment which is purchased by individuals or departments without the knowledge of information systems personnel.

4.1.4 Strategic Goals

The most difficult observable in terms of the cluster of driver technologies is the change in product and service quality and the invention of new products and services, the box at the bottom of Figure 1. Success, which is related to one interpretation of our production function results, may be an observable indicator of these. Our interpretation is that firms that with high levels of measured productivity have achieved one or more of the subgoals at the bottom of the Figure.

In order to calculate productivity, we combined the above data with data from Standard and Poors' Compustat. Measures were created for output, capital, labor, and

[13] It is more difficult to observe the portions of IT expenditure that are distributed throughout the firm (personal computers, small web servers, etc.). It is also more difficult to observe software investments than hardware investments, and it is particularly difficult to observe applications software that would reveal the purposes of business computer systems.

value-added. These let us estimate a production function relationship between value-added and the various inputs following the procedures in Hall (1990) and Brynjolfsson and Hitt (1997). Table 2 provides sample means for these variables.

5 Empirical Results

5.1 Introduction

Our hypothesis that IT, human capital, and decentralized organizational structure are all complements has a number of testable implications for the firm-level data. What we do in this paper is focus on the overall patterns in the data to build a prima facie case that IT, WO and HK all "go together".[14]

First, under plausible assumptions, we would expect levels of each of them to covary in cross-sectional / time series data.[15] If IT is a complement for HK, we should expect firms that for some reason have higher levels of IT than their competitors should, on average, also find it more profitable to hire more educated workers and to train existing workers more intensively. Similarly, if IT is complement for WO, we should expect IT-intensive firms to be more likely to organize production using self-managing teams and delegated decision-making than other firms in the same industry. Likewise, high levels of HK or WO should, all else being equal, be predictive of high levels of the other hypothesized complements.

Second, productivity should be higher in firms that successfully match IT, organizational structure and human capital investments than in those that cannot make such matches. Specifically, productivity should, on average, be higher in firms' which have above-average levels of *both* IT and HK as compared to firms which are above the industry average on one dimension and below average on the other. Other pairwise combinations should also predict productivity levels.

[14] In a related paper (BBH, 1998), we build more structured models of firm-level demand functions for IT and human capital, and also examine a variety of production functions which enable more formal tests of the theory.

[15] Holmstrom and Milgrom (1994) offer a theory of complementarity and a series of observations about the conditions under which co-movements of different organizational practices and factors of production are indicators of complementarity. Athey and Stern (1998) are rightly critical of interpreting co-movements in a cross section of firms as indicating complementarity when there is a possibility of omitted common factors.

Third, in light of the productivity predictions, one can also make some predictions about how the levels of IT, HK and WO should change over time in different firms. Firms with high levels of one or more of the three complements should find it more profitable to invest more aggressively in the remaining elements of the hypothesized complementary system. For instance, for any observed level of IT capital stock, we should see more rapid IT investment in firms with high levels of HK. We should also see more investment in training in firms with high levels of IT.

5.2 Correlations among IT, human capital and workplace organization

As discussed in the data section, we have numerous different measures of firms' IT capital, their employees' human capital and overall workplace organization. The first way we examine the data is simply to consider correlations among these measures. We begin by examining Spearman rank-order correlations among pairs of the relevant variables while controlling for industry, firm size (employment), and the composition of the principal production workers in each firm. The last control is really a production-process one. At the risk of "over-controlling" for factors which may be endogenous to our theory, we include these controls to reduce the role of unobserved heterogeneity in the sample.

In Tables 4 through 8, we show that IT, HK and WO are all highly correlated with each other in our data, regardless of how each concept is measured. One can thus make predictions about, say, a firm's work organization relative to its competitors, if one knows it's IT-intensity or human capital levels, and vice-versa.

5.2.1 IT use is correlated with employees' human capital in firm level data

We find that most measures of IT are significantly correlated with most measures of employees' human capital in our sample of firms (Table 4). The correlation is stronger when the measures of IT are taken from the same organizational survey as the human capital data (first three columns) than when we use the IT measures from the separate CII survey. This probably reflects a better match of the unit of observation.[16] The finding of

[16] The respondents for the organizational practices survey were explicitly asked to consider a representative site for both the HK and IT questions. In contrast, the CI data were for the company as a whole.

a correlation between IT and HK in firm-level data extends findings in previous work, which used more aggregate data (e.g. Autor, Katz and Krueger, 1997).

Classification of employment by job title is also correlated with IT. Firms which employ more managers and especially professionals are more likely to have high levels of IT relative to their industry competitors while those with more blue collar workers tend to have less IT, and vice versa (Table 5). In our framework, the employment job titles can be interpreted as proxies for employee skills, as is common in earlier work, or as characteristics of workplace organization.

5.2.2 IT use is correlated with specific characteristics of workplace organization

In Table 6 we examine the correlations of various measures of IT with our summary measure of decentralization, WO, and with the measures that underlie it. All of the components of WO are individually correlated with IT measures. Interestingly, the strong correlations with self-managing teams and team-building exercises suggest that "people" skills, not just decision-making skills, are important complements of IT.

In these tables, one would conclude that there are significant relationships between IT and human capital and between IT and workplace organization whichever measure of IT was used. There are two further points worth noting. First, PCs are not the strongest correlate for most measures of human capital. Instead, central computer use appears to be a slightly better predictor, which is consistent with an important role for organizational computing and, by inference, organizational impacts. Second, email use is a particularly strong indicator of teams and related practices, as well as of high levels of human capital. This could suggest an important role for communication, as opposed to automation, in driving skill upgrading. Like the other correlations, it may also simply reflect some residual unobserved heterogeneity in the sample.

5.2.3 Human capital is correlated with workplace organization

In turn, the same decentralized workplace organization that is correlated with IT is also is highly correlated with employee human capital (Table 7). Our finding that certain workplace systems are correlated with higher levels of human capital extends and amplifies a result reported by Osterman (1994) who observes "As the skill levels required by an enterprise's technology increase, so does the use of the various work organization innovations."[17]

Some, but not all of the correlation between IT and human capital that we found can be "explained" through their common covariance with differences in organizational structure. When we partial out workplace organization, the correlation between IT and most measures of human capital drops somewhat (Table 8). While the three move together, there is also substantial separate movement and co-movement of the pairs. This is consistent with the view that all three are complements.

Alternative theories in which highly skilled workers or successful managers in particular firms are given IT for nonproductive reasons are implausible here.[18] WO and mainframes are very odd ways to consume a managerial rent or to reward favored classes of workers. This is notably true given that most of WO is ΔWO, and that these organizational changes are notoriously difficult and unpleasant. Mainframes and servers make terrible toys. When queried, the managers in our sample provide a simpler explanation: IT use tends to require more skilled workers and more decentralized decision-making. Indeed, as reported in more detail in our companion paper (BBH, 1998), the greater a firm's experience with IT, the more likely it is to report these effects, and vice-versa.

This argument will be strengthened by the observation that coordinated investments in HK, WO, and IT are more productive than uncoordinated investments, a topic to which we now turn.

5.3 How do various combinations of IT, human capital and workplace organization contribute to output?

If all managers fully understood the potential complementarities among IT, workplace organization and human capital, if their decisions always reflected the profit-maximizing strategies for their firms, and if there were no lags, adjustment costs or

[17] The workplace innovations tracked by Osterman were teams, job rotation, TQM and quality circles. His measure of skills was a dummy variable for whether "the production process requires a high level of skill."

[18] If highly skilled workers and managers cause IT and WO in the cross section of firms (rather than the reverse) for productive reasons, then they are complements in production and our argument is correct.

mistakes in implementing these strategies, then the demand equations IT and for HK would fully reflect the optimal relationships among these factors. Furthermore, under these assumptions, we would not expect to observe any firms that were *not* implementing the optimal combinations of these practices. Of course, one of the reasons that we think studying these relationships is interesting is that we believe that they are not fully understood. With the benefit of hindsight, it is clear that many firms make significant mistakes in their IT investments, organizational strategies or human capital policies.[19] Furthermore, a large number of firms actively experiment with these policy levers in a conscious effort to understand the how to best use the every cheaper processing, storage and communications power delivered by IT. As with any important general-purpose technology, a tremendous amount of organizational and strategic co-invention must accompany technological advances in computing and most managers are fully aware of this need.

Under these conditions, different combinations of inputs will lead to differences in product and service quality in our sample of firms. Under the assumption that higher quality levels will be manifested in increased revenues (due to greater sales, higher unit prices, or both), a production function can help to identify complementarities. Indeed, the production function approach will be most effective to the extent that firms are *not* all employing a well-matched combination of inputs. Thus, this approach provides a valuable counterpart to the correlation results and demand equations, which both provide the strongest results when firms are successfully optimizing.

The theory is quite specific about what we should expect to see. As noted by Milgrom and Roberts (1990), it is not enough to find that firms that invest heavily in all the posited complements have greater output than those that do not. Instead, the theory requires that the increase in output associated with the investment in one complement be greater when other complements are present than when they are not. IT, for example, may be productive on its own, but our theory predicts that it will be *more* productive in firms with high levels of HK, WO or (especially) both.

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[19] See, for instance, Kemerer and Sosa (1991) for a catalog of disastrous IT projects, some running into the tens of millions of dollars. Most of the failures are linked to organizational and strategic errors.

While the productivity analyses depend on at least some firms making the "wrong" choices by investing in one complement without the others, we need not assume that all combinations of inputs are equally like to be observed. Specifically, suppose that managers are attempting to increase firm output quantity and quality by choosing the optimal combinations IT, WO and HK. Suppose further that they are imperfect in these attempts, but do better than mere chance. Then we would expect to find evidence of complementarities both in the correlations, which reflect the partial success in combining IT, WO, and HK, and in the estimated production functions, which reflect the increased value of output generated by the firms that get the combinations “right” relative to those who don't. In this way, we can link differences in firms' choices of IT, WO and HK to their degree of success in achieving their organizational goals.

A natural way to study this is to estimate a production function and examine how various combinations of organizational characteristics affect productivity. Following common practice, we focus on a loglinear specification and its variants. This functional form has the advantage of its simplicity and straightforward interpretation. It is the interaction effects between different inputs that measure complementarities in this framework. Accordingly, we build a model starting from a very simple specification (consistent with Cobb-Douglas production) and adding various sets of interactions. The baseline production function includes controls for industry and year and two types of productive inputs: labor and capital.

We can now easily explore complementarities among various combinations of inputs. For instance, to study how IT and HK combine to affect output we split the sample into four quadrants: 1) High IT-High HK, 2) High IT-Low HK, 3) Low IT-High HK and 4) Low IT-Low HK, and define dummy variables for each of the quadrants, D.

We then run a regression of the form:

$$\log(\text{Output}) = \alpha \log(\text{Labor}) + \beta \log(\text{Capital}) + \delta_{hh} * D_{\text{high-IT*high-HK}} + \delta_{hl} * D_{\text{high-IT *low-HK}} + \delta_{lh} * D_{\text{low-IT*high-HK}} + \delta_{ll} * D_{\text{low-IT*low-HK}} + e$$

The first two terms control for the contributions of the traditional inputs, labor and capital, to output while the next four terms are dummy variables that depend on a firms IT intensity and its human capital levels relative to its industry competitors. In this way, we can estimate the average productivity levels of firms in each quadrant relative to the baseline case of low IT-low HK. The results for δ are shown in Table 9.

As we expected, those firms which combine high levels of IT with high levels of HK are more productive than those which are low on both dimensions. And the differences are not small. The measured output of firms with high levels of IT and more skilled workers is over 4% higher than their industry competitors' with similar levels of labor and capital inputs.[20]

What is especially striking, however, is that low-low also tends to be a relatively high productivity outcome. We normalize the omitted category low-low to zero, so the negative estimates for δ_{hl} and δ_{lh} mean that firms in the off-diagonal cells (low-high or high-low) are less productive than those with low IT and low HK. Thus, high HK is associated with high productivity, but only in firms which also have high IT. HK is not associated with high levels of productivity for firms with low IT. The productivity kick comes from matching IT and HK. This suggests that high levels of IT are most effective in the presence of a trained and educated workforce and conversely.

As noted above, this is exactly the pattern predicted by the complementarities notion. There is a perfectly workable cluster of low-low, old-style firms. They have internal consistency in their mix of complements, what Milgrom and Roberts (1990) call a "coherent combination" of practices. Further, this result argues against heterogeneity arguments as an explanation for the results. While some unobserved firm level shock (free cash flow is the obvious one) could yield positive effects on human capital, IT and productivity at the same time, it would not explain why firms with both low IT and low HK have <u>higher</u> productivity than those with one but not the other.[21] Similarly, this result argues against a "fad" interpretation. The cluster of inputs that go together are clearly

[20] The table shows sample splits for only one measure of HK, namely SKILL. Qualitatively similar results obtain for other measures, such as %COLL, and for related specifications with the output elasticities varying between high and low IT firms.

[21] One can, of course, construct a more intricate theory to explain the results. In this case, there could be correlated shocks to the productivities of the factors at the firm level that are confined to certain ranges of use of the factors in different ways in different firms. In empirical science, there is always an alternative explanation of this form; this one is distinctly pre-Copernican in structure.

related to increases in output quantity or price (perhaps because of service quality). Thus they cannot be merely an inefficient fad.[22]

Similar results also hold when the regression includes WO and its interaction with HK (in Table 9B) instead of IT and HK. Firms with more of the characteristics of the new work organization are more productive if they also have highly skilled workers. However, firms attempt the new work organization without more skilled workers than their industry peers, or which employ more skilled workers but not the new work organization, are notably less productive than firms which simply adopted a Low WO-Low HK strategy. As before, this is most easily explained as evidence of complementarities.

Finally, comparing interactions of WO and IT (in Table 9C) leads to a similar story. In this case, the off-diagonal firms (high-low and low-high) are not actually less productive than the low-low firms, instead, the productivity advance to getting one but ont the other is positive but small and insignificant. Shifting from low levels of IT to higher levels of IT is associated with a greater increase in productivity for high WO firms than for low WO firms, and conversely, WO appears to be most productive in the presence of high levels of IT.

As noted above, in each table the sample is split at the median firm so that approximately half of the firms are in each "high" group and half are in each "low" group. However, it is clear that the firms are not evenly distributed among all four quadrants. As one might expect if our explanation is correct, a majority of firms avoid the low productivity quadrants in favor of the "high-high" or "low-low" quadrant. For instance, there are over twice as many firms in the "high IT-high HK" quadrant as in the "high IT-low HK" quadrant". This is of course consistent with the earlier correlation analyses (Section 5.2), but we can now see that this pattern is also consistent with the hypothesis that firms to choose their practices at least in part to increase productivity.

While the 2x2 tables present a simple way to see the productivity levels associated with various combinations of IT, HK and WO, much the same story is evident in more structured models such as those we explore in our companion paper (BBH,

[22] We exclude the fancier theory of an inefficient fad whose incidence is somehow confined to

1998). When various interaction terms are included in a log-linear specification, alone or in combination, the results indicate that IT, HK and WO are complements. This is true when alternative measures of the each of the basic work practices are examined, when we instrument the endogenous variables to control for endogeneity and to a limited extent even when three-way interactions are explored, although collinearity limits the reliability of such analyses.

5.4 How are IT, HK and WO changing over time?

Levels of investment in both IT and HK are well known to be increasing over time. The biggest changes are in IT, where impressive advances in the underlying science and engineering of the technology has led to sharp improvements in both capabilities and costs. As a result, real investment in IT has grown at double-digit rates for several decades and current levels dwarf those of even a few years ago. Meanwhile, the skill levels of the workforce have also increased, at least according to such metrics as the proportion of college graduates in the workforce. Data on changes in WO are harder to come by, although there seems to be a consensus that many of the practices we measure are becoming more common (See e.g. Ichniowski et al., 1996, Osterman 1994).

While the levels of IT, HK and WO may all be increasing, all firms do not necessarily adopt them at the same rate. In fact, the complementarities theory predicts that firms which are further along in one practice should be more likely to adopt the other practices, *ceteris paribus*. The productivity analyses empirically support the notion that such a policy will have the greatest rewards.

We can test this implication more directly by looking at investments, not just levels, of the work practices. We do not have direct measures of HK or WO over time, but we do have measures of investments in training and policies of screening new employees based on education at the end of the sample period. These measures can be interpreted as investments in HK. At noted earlier, we find that most measures of IT are correlated with greater *investments* in human capital (Table 4, middle rows). IT can predict greater investments in human capital (HKI) even when we control for current levels of human capital (by including SKILL and EDUC as partial covariates in the

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successful firms. That is, of course, possible, if peculiar.

bottom rows of the table). Although HK is changing much most slowly than IT, this result is consistent with the hypothesis that IT-intensive firms are attempting to move toward a new cluster of complements, relative to less IT-intensive firms.

The earlier results indicated that firms with high levels of human capital and work organization are more likely to also have high levels of IT. We can also examine a dynamic version of this question by adding interaction terms between a time trend and two human capital and organizational structure measures. We can undertake this partially dynamic analysis as we have IT data for each year of our sample period, but our measures of human capital and workplace organization are only available for the end of the period. In Table 10, we see that for any given set of prices and business conditions, firms with more decentralized decision-making (WO) tend to invest more rapidly in IT than their competitors. However, we do not find that HK is a particularly strong predictor of IT investments (as opposed to IT levels) even though IT levels can predict HK investments.

As with our other results, the most direct interpretation is complementarities. The interactions with time pick up changes in IT over time. WO is changing in many of our sample firms and, where it is changing, IT is growing. In one story, WO is a new organizational invention[23] (or IT-enabled WO is a new organizational invention). Those firms that have moved forward in WO have also moved forward on the other complements, by this interpretation.[24] HK is more stable, and so the level of HK at the end of the period is not a good predictor of changes in IT. This would suggest that the IT-HK complementarity is closer to equilibrium while we are observing firms actively investing in both WO (narrow definition) and complementary IT.

In summary, we view these dynamical results as consistent with the complementarity story. While not all of the complements are changing at the same rate,

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[23] This is essentially the view that Ichniowski et al. (1996) put forth in their summary of the literature on innovations in workplace organization.

[24] Accordingly, it is not a criticism to note a weaker correlation between WO and IT in the early part of the sample (since our WO data are only contemporaneous with IT at the end of the sample period). Similarly, it is not an econometric criticism that WO(1995) is a measure of WO(t) with an error that declines over time, rather, this econometric remark is closely linked to the economics of our interpretation.

[25] Indirect evidence for this fact is the high gross marginal products found for IT when standard production functions are estimated using firm level data (Brynjolfsson and Hitt, 1995, 1996, Lichtenberg, 1995).

it appears that one can make some predictions about a firm's investment rates in one complement by looking at the levels of other complements in that firm.

5.5 Relationship to Earlier Work

Most earlier work at the *industry level* finds complementarity between IT and HK (AKK 1997). The incompleteness, there, and the advance here, is getting inside the black box of the firm first with the WO data and second with the managerial queries just reported. This illuminates the mechanisms at work in a way that makes the technological causation story more complete and thus more refutable; when unrefuted, more convincing.

Earlier work at *the individual worker* level has been at best ambiguous in its results about IT-HK complementarity. Individual workers who use computers do command higher wages (Krueger (1993)). Yet it appears that both the higher wages and the computers may be given to workers who are already particularly productive, rather than (or in addition to) the computer making the worker more productive (DiNardo and Pischke (1997)). Here we have considerable evidence against a nonproductivity alternative direction of causation argument at the *firm* level. The firm-level equivalent would be that *firms* with particularly high levels of HK got, for some reason not related to production complementarities, WO and IT. The analogy to the individual-worker theory is obviously false; WO and mainframes make poor "rewards" for the reasons we just argued. Finally, at the firm level we have more direct evidence on the productivity of using the factors together. Moving closer to the actual demanding unit, the firm, permits investigation of the hypotheses better than at the worker or industry level.

6 Implications

Strong complementarity among human capital, new forms of workplace organization, and IT is a finding with important implications for the whole economy. The three complementary factors play different roles.

(IT) The real price of IT has been falling rapidly and will continue to fall for at least a decade. This shifts firms in the direction of using all three complements. This is the route by which IT and the workplace organization changes it enables become skill-biased technical change.

(HK) The supply curve for more skilled workers is rising. The IT-driven skill-biased technical change has driven changes in relative wages, hours, and earnings.

(WO) Finally, the third complement, workplace organization, is characterized by very substantial adjustment costs, as is changing in output quality. Firms must co-invent the specific organizational changes and specific new product qualities that work in their particular circumstances, a nontrivial challenge.

Computer and other information technology prices have been falling steadily, tending to raise demand not only for IT capital but also for the invention of new organizational forms and for new services or new levels of quality. The demand for all three is by no means automatic, however, because of those substantial adjustment costs. At any given moment, we expect to see variety in a cross section of firms in the degree to which they have adopted the three complements. Leading firms will have high levels of all three complements; trailing firms will have low levels of all three complements. Some firms will be further along on some dimensions than on others due to mistakes or random factors that influence their adoption.

What's more, the underlying complementarities in the systems adopted by the leading firms are undoubtedly far more complex and intricate than those we can observe in our data. For instance, Brynjolfsson, Renshaw and Van Alstyne (1997) studied one firm's transition from traditional manufacturing to modern, computer-intensive manufacturing and found not only dozens of complementarities but also several mistakes, reversals and abortive attempts to implement incomplete clusters of complements. When the firm finally got the new work system working smoothly, they literally painted the factory windows black to prevent competitors from quickly imitating their success. This supports the hypothesis that one of the barriers that prevents competitors from quickly imitating the most successful computer users is the subtlety and complexity of the organizational co-inventions needed to harness this revolution in computer power.[25]

Like econometricians, rival managers may be able to observe the broad outlines of a successful strategy without knowing the myriad details necessary to implement it effectively. This is consistent with the large adjustment costs associated with IT, which have been found to be primarily the costs of adjusting the complementary WO, not the IT itself (cf. Bresnahan and Greenstein (1997), Brynjolfsson and Hitt (1997), and especially Ito (1996) on this point),[26] and suggests that merely pointing the way toward a "high performance work organization" will rarely be sufficient to get trailing firms to adopt the new system.

In addition to these adjustment costs, rising wages of highly skilled labor also slow the diffusion of the cluster of complements (and presumably offer a powerful incentive for inventing ways to use IT and organizational forms that economize on skill.) Neither of these counter-effects, however, reverses the trend to the cluster of complements. They simply slow it, in large measure by limiting the number of firms using the cluster of complements.

We therefore believe that the current cross-firm variety in adoption of the three-way cluster of innovations embodies a forecast of the future. An easy prediction is that IT prices will continue to fall and IT performance will continue to improve (notably in the data networking area). As a result, more and more firms will find the cluster of complements worth adopting. In parallel, firms that are now experimenting or unsure will increasingly overcome the costs and delays associated with the organizational change. Over time, therefore, more firms will come to look like those using the cluster of complements: IT-intensive, changed workplace organization, and high human capital. The aggregate implication is that the recent tendency toward skill-biased technical change will continue.

7 Conclusion

In this paper, we combine and extend two distinct research streams. One, developed primarily by labor economists, links IT to the increased demand for skills. Another, developed primarily by information systems researchers, links IT to changes in

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[26] If we were to expand the definition of IT to include applications software and the training and reorganization needed to use it effectively, it would become more fixed in the short run. Our observables, however, correspond to the adjustment cost relationships described in the text. There might well be a different way to divide the cluster of complements, focussing on applications of IT rather than IT hardware, which would yield a more detailed and nuanced view of the pattern of adjustment costs than we can provide here. That, however, would call for more detailed data on the software side of IT.

organization and output quality. We hypothesize that the increased demand for skilled labor is related to a particular cluster of technological change involving not only increased use of IT, but also changes in workplace organization and changes in product and service quality. The most common combinations of IT-enabled organizational and strategic change increase the relative demand for skilled workers.

We find that the empirical evidence is broadly consistent with our hypothesis as well as prior theoretical and empirical work on IT and labor demand and IT and organization. In particular, our analysis of firm-level data suggests that IT use is correlated with increases in the demand for various indicators of human capital and workforce skills. IT use is also correlated with a pattern of work organization involving more decentralized decision-making and greater use of teams. Increases in firms' IT capital stock are associated with the greatest increases in output in firms which also have high levels of human capital or decentralized work organization, or both. However, firms which implement only one complement without the others are often less productive than firms which implement none at all. Firms with high levels of some complements are more likely to invest in other complements. In addition, in our companion paper (BBH, 1998) we show that these empirical facts are consistent with the widespread perception among the managers in our sample. When asked directly, these managers reported that IT is skill increasing, and this tendency is particularly pronounced in high human capital, IT-intensive, and decentralized firms.

The combination of computerization, workplace organization and increased demand for skilled workers appears as a cluster of changes in modern firms, almost certainly because they are complements. This has two implications. First, many of the recent s changes in the structure of the corporation and the demand for human capital have a common origin in technological change, technological change which shows no sign of abating. As a result, the specific mechanisms of skill-biased technical change now and in the future can be better understood by more closely studying the nature of IT-enabled organizational change in firms.

8 Bibliography

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

Athey, S. and S. Stern, (1998) "An Empirical Framework for Testing Theories about Complementarities in Organizational Design". NBER working paper 6600.

Attewell, P. and J. Rule (1984) "Computing and Organizations: What We Know and What We Don't Know." Communications of the ACM 27(December): 1184-1192.

Autor, David, Lawrence F. Katz and Alan B. Krueger. (1997) "Computing Inequality: Have Computers Changed the Labor Market?" revised, March.

Barras, Richard. (1990) "Interactive Innovation in Financial and Business Services: The Vanguard of the Service Revolution," Research Policy No. 19.

Bartel, A. and Lichtenberg, (1987) "The Comparative Advantage of Educated Workers in Implementing New Technology", Review of Economics and Statistics, 64 1-11.

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

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

Bound, John and Johnson, George. (1992) "Changes in the Structure of Wages in the 1980s An Evaluation of Alternative Explanations," American Economic Review 82,3: 371-392.

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

Bresnahan, T. and S. Greenstein (1997) "Technical progress and co-invention in computing and in the uses of computers," Brookings Papers on Economic Activity, Micro, pp. 1-83.

Bresnahan, T., Brynjolfsson, E. and L. Hitt (1998). "Information Technology, Workplace Organization and the Demand for Skilled Labor: Firm Level Evidence." Mimeo. MIT, Stanford and Wharton.

Brynjolfsson, E. and L. Hitt (1995). "Information Technology as a Factor of Production: The Role of Differences Among Firms." Economics of Innovation and New Technology 3 (4): 183-200.

Brynjolfsson, E. and L. Hitt (1996). "Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending" Management Science (April).

Brynjolfsson, E. and L. Hitt (1997). "Information Technology and Organizational Design: Evidence from Firm-level Data" MIT Sloan School Working Paper.

Brynjolfsson, E., A. Renshaw and M. V. Alstyne. (1997) "The Matrix of Change," Sloan Management Review, Winter.

Crowston, Kevin and Malone, Thomas W. (1988), "Information Technology and Work Organization," Chapter 49 in: M. Helander, ed., Handbook of Human-Computer Interactions. Elsevier Science, Amsterdam, pp. 1051-1070.

Davenport, Thomas H., and James E. Short. (1990) "The New Industrial Engineering: Information Technology and Business Process Redesign." Sloan Management Review 31.4: 11-27.

DiNardo, John and Jörn-Steffen Pischke. (1997) "The Returns to Computer Use Revisited: Have Pencils Changed the Wage Structure Too?" Quarterly Journal of Economics 1 1 2 (February).

Gottschalk, Peter. (1997) "Inequality, Income Growth, and Mobility: The Basic Facts," Journal of Economic Perspectives 11, 2 (Spring): 21-40.

Griliches, Z. (1969). "Capital-Skill Complementarity." The Review of Economics and Statistics 51(4): 465-468.

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

Hamermesh, Daniel S., Labor Demand Princeton, NJ: Princeton University Press, 1993.

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

Holmstrom, B. and P. Milgrom (1994). "The Firm as an Incentive System." American Economic Review 84(4, September): 972-991.

Howell, C., and E. Wolff, (1991) "Trends in the Growth and Distribution of Skills in the U.S. Workplace," Industrial and Labor Relations Review, April.

Ichniowski, C. Thomas A. Kochan, David Levine, Craig Olson and George Strauss, (1996) "What works at work: Overview and Assessment", Industrial Relations, Vol. 35, No. 3 (July). P. 299-333.

Ichniowski, C., K. Shaw and G. Prennushi, "The Effects of Human Resource Management Practices on Productivity." American Economic Review, June, 1997.

Ito, Harumi, Essays on Investment Adjustment Costs, Ph.D. Dissertation, Stanford University, September 1996.

Jensen, M. and W. Meckling, (1992) "Knowledge, Control and Organizational Structure", in Contract Economics, L. Werin and H. Wijkander, Editors., Basil Blackwell: Cambridge, MA. p. 251-274.

Katz, Lawrence F. and Kevin M. Murphy. (1992) "Changes in Relative Wages, 1963-1987: Supply and Demand Factors," Quarterly Journal of Economics 107 (February): 35-78.

Kemerer, C. F. and G. L. Sosa, (1991) "Systems Development Risks in Strategic Information Systems." Information and Software Technology 33(3): 212-223.

Krueger, Alan B. (1993) "How Computers Have Changed the Wage Structure? Evidence from Micro Data," Quarterly Journal of Economics (February): 33-60.

Krugman, Paul, and Robert Z. Lawrence. (1993) "Trade, Jobs, and Wages," NBER WP No. 4478, September.

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

Levy, Frank and Richard Murnane. (1996) "With What Skills Are Computers a Complement?" American Economic Review, 86 (May): 258-262.

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

Malone, T. and Rockart, J. (1991), "Computers, Networks and the Corporation," Scientific American, Vol. 265(3): 128-136.

Malone, T., Yates, J. and Benjamin, R. "Electronic Markets and Electronic Hierarchies." Communications of the ACM 30(6): 484-497.

Mendelson, Haim and Ravi Pillai, "Clockspeed and Informational Response: Evidence from the Information Technology Industry", Manuscript, 1998.

Milgrom, P. and J. Roberts (1990). "The Economics of Modern Manufacturing: Technology, Strategy, and Organization." American Economic Review 80(3): 511-528.

Murphy, Kevin M. and Welch, Finns. (1993) "Lessons from Epirical Labor Economis: 1972-1992. Inequality and Relative Wages," American Economic Review, 83, 2.

Orlikowski, W. J. (1992). Learning from Notes: Organizational Issues in Groupware Implementation. in Conference on Computer Supported Cooperative Work. J. Turner and R. Kraut. Toronto, Association for Computing Machinery: 362-369.

Osterman, P. (1994). "How Common is Workplace Transformation and Who Adopts It?" Industrial and Labor Relations Review 47(2): 173-188.

Scott Morton, Michael S. (Ed.) (1991), The Corporation of the 1990s: Information Technology and Organizational Transformation, Oxford University Press.

Simon, Herbert A., "Applying Information Technology to Organization Design." Public Administration Review, (1973), p. 268-78.

Simon, Herbert A., "Designing Organizations for an Information-Rich World," in Computers, Communications, and the Public Interest, Martin Greenberger, ed. Baltimore: The Johns Hopkins Univ. Press, 1971, pp. 40-41.

Wolff, Edward N. (1996) "The Growth of Information Workers in the U.S. Economy, 1950-1990: The Role of Technological Change, Computerization, and Structural Change," The C.V. Starr Center for Applied Economics, New York University.

Williamson, Oliver E. 1979. Transaction-Cost Economics: The Governance of Contractual Relations. Journal of Law and Economics 22 (October):233-261.

Zuboff, Shoshana (1988) In the Age of the Smart Machine: The Future of Work and Power, New York: Basic Books.

9 Tables and Figures

Table 1: Organizational Practice Survey Variables

	Range	Variable	N	Mean	Std. Dev.
Team-Based Work Organization					
Use of Self-Managing Teams	1-5	SMTEA	345	2.11	1.13
Use of Employee Involvement Groups	1-5	QUALC	345	2.85	1.21
Use of Team Building Activities	1-5	TEAMB	345	2.95	1.17
Promote for Teamwork	1-5	PROTE	345	3.59	0.95
Breadth of Jobs	1-5	BROAD	345	3.25	0.99
Individual Decision Authority					
Who Decides Pace of Work (3=workers)	1-3	PACE	345	1.33	0.37
Who Decides Method of Work (same)	1-3	METH	345	1.39	0.38
Human Capital (Levels)					
Skill Level of Work	1-5	SKILL	345	3.60	0.86
Education Level	1-5	EDUC	345	2.48	0.66
Workers w/ High School or Less Ed.	0-100%	%HSED	263	59.3%	27.8%
Workers with Some College Education	0-85%	%SCED	263	23.3%	17.5%
Workers Completed College	0-100%	%COLL	263	17.4%	21.0%
Human Capital Investment					
Pre-Employment Screen for Education	1-5	SCNED	345	3.31	0.89
Training (% workers involved)	0-100%	TRAIN	345	48.0%	36.1%
Cross-train Workers	1-5	XTRAI	345	3.16	0.98
Production Worker Composition					
Blue Collar (fraction of jobs listed)	0-100%	PRBL	345	61.9%	46.2%
Clerical (fraction of jobs listed)	0-100%	PRCL	345	31.4%	43.4%
Professional (fraction of jobs listed)	0-100%	PRPF	345	4.6%	17.5%
Workforce Composition					
Unskilled Blue Collar (%)	0-95%	%US	337	18.4%	21.4%
Skilled Blue Collar (%)	0-85%	%SK	337	24.7%	21.1%
Clerical (%)	0-80%	%CL	337	19.4%	17.6%
Professionals (%)	0-90%	%PF	337	20.7%	16.8%
Managers (%)	0-50%	%MG	337	16.8%	8.5%

Source: Authors' Survey. Survey Details Appear in Bresnahan, Brynjolfsson and Hitt (1998)

Table 2: IT and other Inputs and Outputs

	Variable	N	Mean	Std. Dev.
CII Survey				
Log(IT Capital)	LITCAP	333	3.07	1.66
Total MIPS (Millions of instructions/sec.)	MIPS	333	2,624	8,737
Total PCs	TOTPC	333	4,560	10,997
Organizational Survey				
Degree of Computerization of Work	COMP	343	3.28	1.11
% Workers using General Purp. Computers	%GP	290	53.0%	33.8%
% Workers using E-mail	%EMAIL	290	31.0%	32.2%
Compustat (all years pooled)*				
log(Output)	LOUTPUT	2466	2,431.59	0.99
log(Value Added)	LVA	2466	946.53	1.02
log(Labor Expense)	LLABOR	2466	530.33	1.08
log(Non-IT Capital)	LNITCAP	2466	1,771.53	1.39
log(Employment)	LEMPLOY	2466	14.41	1.09
log(IT Capital)	LITCAP	2466	11.86	1.42

* - Standard deviation is in log(millions of dollars), while the geometric mean is reported in millions of dollars.

Table 3: Definitions of Composite Variables

Description	Variable	Formula
Work Organization	WO	SMTEA+QUALC+TEAMB+PROTE+ PACE+METH
Human Capital Investment	HKI	SCNED+TRAIN+XTRAI
Composite Decision Authority	DA7	PACE+XSCHED+XDIST+METH+ XPROB+XCUST+XCOMPL

All composites are formed by summing standardized values (except the Information Worker Percentage). The sum is then restandardized to mean 0, unit variance.

Table 4: Correlations between IT and Human Capital

Measure (scale in parenthesis)	%GP	% EMAIL	COMP	ITCAP	MIPS	TOTPC
Skills/Education (N=371)						
Skill Levels (SKILL)	(+)***	(+)***	(+)***	(+)	(+)***	(+)**
Education (EDUC)	(+)**	(+)***	(+)***	(+)	(+)	(+)
Education Distribution (N=237)						
High School Education (%HSED)	(-)***	(-)***	(-)***	(-)*	(-)***	(-)***
College Graduate (%COLL)	(+)***	(+)***	(+)***	(+)	(+)	(+)
Skill Acquisition (N=370)						
Training (TRAIN)	(+)***	(+)**	(+)***	(+)**	(+)***	(+)**
Screen for Education (SCNED)	(+)*	(+)***	(+)***	(+)***	(+)***	(+)***
Skill Acquisition (controlling for SKILL and EDUC)						
Training (TRAIN)	(+)**	(+)*	(+)***	(+)***	(+)***	(+)***
Screen for Education (SCNED)	(+)	(+)	(+)**	(+)***	(+)***	(+)***

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (EMPLOY) and production worker composition (PRBL, PRCL). Sample size varies due to non-response. Key: (+) positive correlation; (-) negative correlation; * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 5: Correlations between IT and Workforce Composition

Measure (scale in parenthesis)	%GP	% EMAIL	COMP	ITCAP	MIPS	TOTPC
Workforce Composition (N=303)						
Clerical (%CL)	(-)	(+)	(-)	(-)	(-)	(-)
Unskilled Blue Collar (%US)	(-)***	(-)***	(-)***	-.08	(-)**	(-)
Skilled Blue Collar (%SK)	(-)	(-)	(+)	(+)	(+)	(+)
Managers (%MG)	(+)**	(+)**	(+)*	(+)**	(+)**	(+)
Professionals (%PF)	(+)**	(+)***	(+)***	(+)***	(+)***	(+)***

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (EMPLOY) and production worker composition (PRBL, PRCL). Key: (+) positive correlation; (-) negative correlation; * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 6: Correlations between IT and Work Organization

Measure (scale in parenthesis)	%GP	% EMAIL	COMP	ITCAP	MIPS	TOTPC
Our Main Measure						
Decentralization (WO)	(+)***	(+)***	(+)***	(+)***	(+)***	(+)***
Subcomponents of WO						
Self-Managing Teams (SMTEA)	(+)***	(+)***	(+)***	(+)***	(+)***	(+)***
Employee Inv. Grps. (QUALC)	(+)***	(+)***	(+)	(+)	(+)	(+)
Team Building (TEAMB)	(+)***	(+)***	.13**	(+)***	(+)***	(+)***
Promote for Teamwork (PROTE)	(+)**	(+)**	(+)**	(+)	(+)*	(+)
Pace of Work (PACE)	(+)*	(+)*	(+)**	(+)	(+)	(+)
Method of Work (METH)	(+)***	(+)***	(+)***	(+)***	(+)***	(+)***
Other Organizational Structure Measures						
Broad Jobs (BROAD)	(+)***	(+)***	(+)***	(+)	(+)**	(+)*
Scheduling of Work (XSCHED)	(+)***	(+)***	(+)***	(+)*	(+)***	(+)**
Distrib. Work to Wrkrs. (XDIST)	(+)*	(+)***	(+)***	(+)*	(+)**	(+)**
Production Problems (XPROB)	(-)	(+)	(+)	(+)	(+)	(+)
Customer Interaction (XCUST)	(+)**	(+)*	(+)	(+)	(+)	(+)
Handling Complaints (XCOMPL)	(+)***	(+)***	(+)**	(+)	(+)	(+)
Composite of 7 measures (DA7)	(+)***	(+)***	(+)***	(+)*	(+)**	(+)***
Individual Control (ICDA)	(+)**	(+)***	(+)***	(+)*	(+)**	(+)**

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (EMPLOY) and production worker composition (PRBL, PRCL). N=240-372, due to non-response and some measures limited to second and third wave surveys. Key: (+) positive correlation; (-) negative correlation; * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 7: Correlations between Human Capital and Work Organization

Measure (scale in parenthesis)	SKILL	EDUC	%COLL	SCNED	TRAIN
Our Main Measure					
Decentralization (WO)	(+)***	(+)***	(+)***	(+)***	(+)***
Subcomponents of WO					
Self-Managing Teams (SMTEA)	(+)***	(+)**	(+)***	(+)***	(+)***
Employee Inv. Grps. (QUALC)	(+)***	(-)	(+)	(+)	(+)***
Team Building (TEAMB)	(+)***	(+)	(+)**	(+)***	(+)***
Promote for Teamwork (PROTE)	(+)**	(+)	(+)	(+)	(+)
Pace of Work (PACE)	(+)**	(+)***	(+)***	(+)***	(+)
Method of Work (METH)	(+)***	(+)***	(+)***	(+)***	(+)*
Other Measures of Organizational Structure					
Broad Jobs (BROAD)	(+)***	(+)***	(+)**	(+)***	(+)
Scheduling of Work (XSCHED)	(+)***	(+)	(+)	(+)**	(+)**
Distrib. Work to Wrkrs. (XDIST)	(+)***	(+)*	(+)	(+)**	(+)*
Production Problems (XPROB)	(+)**	(-)	(-)	(+)	(+)
Customer Interaction (XCUST)	(+)	(-)	(-)	(+)	(+)***
Handling Complaints (XCOMPL)	(+)	(+)*	(+)	(+)	(+)***
Composite (DA7)	(+)***	(+)	(+)***	(+)**	(+)***
Individual Control (ICDA)	(+)***	(+)	(+)***	(+)***	(+)*

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (EMPLOY) and production worker composition (PRBL, PRCL). N=240-372, due to non-response and some measures limited to second and third wave surveys. Key: (+) positive correlation; (-) negative correlation; * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 8: Correlations between IT and Human Capital, Controlling for Work Organization (WO)

	%GP	% EMAIL	COMP	ITCAP	MIPS	TOTPC
Skills/Education (partialling WO)						
Skill Levels (SKILL)	(+)*	(+)***	(+)***	(+)	(+)	(+)
Education (EDUC)	(+)**	(+)***	(+)***	(-)	(+)	(-)
High School Education (%HSED)	(-)***	(-)***	(-)***	(-)	(-)**	(-)**
College Graduate (%COLL)	(+)***	(+)***	(+)***	(+)	(+)	(+)
Same Analysis without controls						
Skill Levels (SKILL)	(+)***	(+)***	(+)***	(+)	(+)***	(+)**
Education (EDUC)	(+)**	(+)***	(+)***	(+)	(+)	(+)
High School Education (%HSED)	(-)***	(-)***	(-)***	(-)*	(-)***	(-)***
College Graduate (%COLL)	(+)***	(+)***	(+)***	(+)	(+)	(+)

Spearman partial rank order correlations controlling for industry (9 sector dummy variables), employment (EMPLOY) and production worker composition (PRBL, PRCL). First four rows also include WO as a covariate. Key: (+) positive correlation; (-) negative correlation; * - p<.1, ** - p<.05, *** - p<.01; test is against the null hypothesis that the correlation is zero.

Table 9: Productivity with Matches and Mismatches on Complements

Table 9A: IT x HK (As measured by ITCAP and SKILL, respectively)

IT \ HK	Low	High
High	-.0293 (.0221) N=552	.0422 (.0199) N=762
Low	0 (N/A) N=561	-.0321 (.0174) N=358

Standard Error in parenthesis; estimates are the δs as shown in the equation.
Pearson chi-square Test for Association: χ^2=82.4 (p<. 001)
Number of firms in each half of the table is unbalanced due to ties and discrete scales (SKILL)

Table 9B: HK x WO (As measured by SKILL and WO, respectively)

HK \ WO	Low	High
High	-.0481 (.0208) N=492	.0372 (.0165) N=822
Low	0 (N/A) N=627	-.0522 (.0178) N=284

Standard Error in parenthesis
Pearson chi-square Test for Association: χ^2=211 (p<. 001)
Number of firms in each half of the table is unbalanced due to ties and discrete scales (SKILL, WO)

Table 9C: IT x WO (As measured by ITCAP and WO, respectively)

IT \ WO	Low	High
High	.00356 (.0179) N=448	.0664 (.0197) N=664
Low	0 (N/A) N=671	.00153 (.0199) N=442

Standard Error in parenthesis
Pearson chi-square Test for Association: χ^2=89.0 (p<. 001)
Number of firms in each half of the table is unbalanced due to ties and discrete scales (WO)

Table 10: Changes in IT demand as a function of human capital and organization - controlling for workforce composition

Dependent Variable	log(ITCAP)	log(ITCAP)	log(ITCAP)
Specification / Variable	Base+ WO	Base+ Education+ WO	Base+Ed.+ WO w/o WOxTime
Worker Skill x Time (SKILL x YEAR)	.000255 (.00759)	-.0194 (.0220)	-.00557 (.0203)
College Ed. x Time (%COLLxYEAR)		.00656 (.0210)	.0109 (.0207)
WO x Time (WO x YEAR)	.0183*** (.00766)	.0358 (.0219)	
Worker Skill (SKILL)	.0438*** (.0191)	.0560*** (.0247)	.0543*** (.0247)
College Education (%COLL)		.0388 (.0276)	.0392 (.0277)
Decentralization (WO)	.0668*** (.0186)	.0876*** (.0238)	.0890*** (.0238)
log(Value-Added) log(VA)	.647*** (.0186)	.600*** (.0219)	.599*** (.0219)
Professionals (%PF)	.133*** (.0206)	.0967*** (.0291)	.0958*** (.0291)
Controls	Sector Year Composition (PRBL, PRPF %MG, %CL, %SK) %SCED	Sector Year Composition (PRBL, PRPF %MG, %CL, %SK) %SCED	Sector Year Composition (PRBL, PRPF %MG, %CL, %SK) %SCED
R^2	53.7%	51.0%	50.9%
N	1854	1331	1331

Key: * - p<.1, ** - p<.05, *** - p<.01
All variables standardized to mean 0, unit variance except interaction terms which represent a standardized variable multiplied by a mean 0 time measure (units are years).