The Substitution of Information Technology for Other Factors of Production: A Firm Level Analysis

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Fueled by its constant technological and price improvements, information technology (IT) is displacing other inputs in the production of goods and services. By 1994, IT accounts for over 15% of fixed investments by the U.S. private sector, and the ratio of new IT investments to labor costs is approaching 5% (1990 dollar basis). The ability to take advantage of improvements in IT is determined in part by the substitutability of IT for other factors of production.

This paper builds on the empirical framework of Brynjolfsson and Hitt (1995) and extends it to jointly estimate output and substitution elasticities using the CES-translog production function. Our primary source of IT-related data is the IDG/*Computerworld* annual survey data on IS spending by large U.S. firms, for the period 1988 to 1992, previously analyzed by Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995).

A key result is that IT capital is a net substitute for both ordinary capital and labor, suggesting that the factor share of IT in production will grow to more significant levels over time. We confirm earlier findings of positive returns to IT investment for this data set. Further, we find excess returns on IT investment relative to labor input and some evidence of excess returns relative to ordinary capital. Taken together, these results shed new light on the productivity paradox of IT and on the growth of information intensity across the economy as firms take advantage of the continuing improvements in IT.
(*Information Technology; Productivity; Substitutability; Computers; IT Investments; Productivity Paradox*)

1. Introduction

The phenomenal price and performance improvements in Information Technology (IT), that fuel the "information revolution," have also led to the overarching displacement of non-IT inputs in the production of goods and services. Over the past few decades, IT has accounted for an increasing share of new investments by the U.S. business sector. Based on the BEA asset category "Office, Computing and Accounting Machinery," IT investment has increased at the average rate of 7.4% per annum (1990 dollar basis) in the period from 1960 to 1994. By comparison, the overall output of the economy (GNP) has increased at only about 3% per annum. Figure 1 shows that the share of IT in nonresidential fixed investment has grown from 0.4% in 1960 to 15.5% in 1994, while the ratio of IT investments to labor costs, has increased from 0.4% in 1980 to 4.7% in 1994.[1] IT

[1] The BEA Office, Computing and Accounting Machinery (OCAM) asset category primarily includes computers and peripheral equipment, while nonresidential fixed investments include, in addition to OCAM, durable and transportation equipment, nonresidential structures, furniture and fixtures. These are available in both current and constant dollars from BEA (1995). Labor cost is taken to be the aggregate wage

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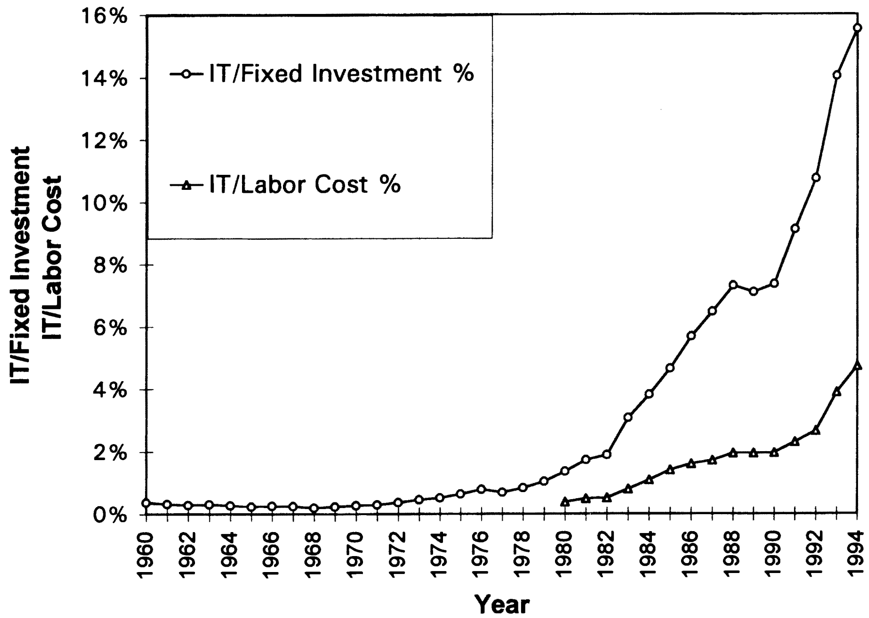
Figure 1 **IT Investment as a Percentage of Aggregate Annual Fixed Investment and Labor Cost (1990 Dollar Basis)**



IT refers to BEA asset category Office Computing and Computing Machinery. Source: BEA (1995) and Council of Economic Advisors (1995).

intensity, as measured by both IT investment per employee, and IT as a percentage of total fixed investments (Figures 2 and 3, respectively), has steadily increased in every sector of the economy.[2]

The fact that the financial sector appears to be a clear leader in the growth of IT intensity is not surprising. It was among the first to incorporate electronic data processing in its operations, through check handling, bookkeeping, credit analysis and automated teller machines (Franke 1987). Across all industry sectors, the earliest applications of IT were directed toward the reduction of personnel costs in such labor-intensive operations as accounting, purchasing and payroll. Since then, computing and communications technologies have affected all functions of the modern corporation, gradually displacing traditional labor and capital inputs, through such applications as electronic order entry, electronic data interchange, office automation, telecommuting, expert systems, robotics, object-oriented programming, and point-of-sale settlement, among others. The recent trend of IT-led restructuring and reengineering has accelerated the transformation of business processes.

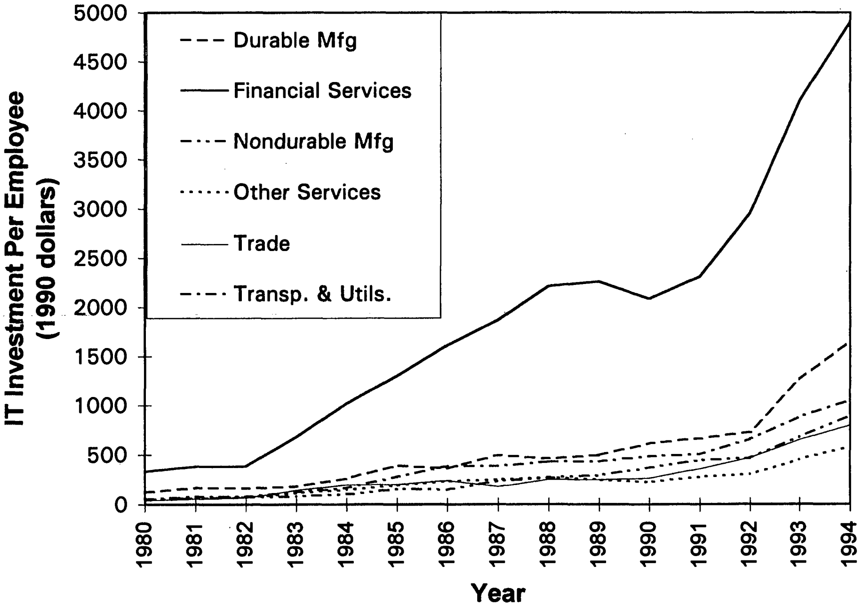
By substituting IT for labor or ordinary capital, organizations seek to capitalize on the vastly superior price and performance improvements in IT relative to these other inputs. According to Lau and Tokutsu (1992), the quality-adjusted price of computer assets has decreased at the average annual rate of 20%, relative to the price of other capital goods, over the period 1960–1992. The ability to take advantage of the economic opportunities created by improvements in IT is determined, in part, by the substitutability of IT for other inputs. The primary purpose of this paper is to estimate IT substitutability, relating it to structural firm characteristics on the one hand and to the productivity of inputs on the other. We develop a flexible production function framework to jointly estimate output and substitution elasticities, using a recent sample of firm level data.

A pioneering work in the context of input factor substitution is the development of the constant elasticity of substitution (CES) production function by Arrow et al. (1961). They used the CES production function to

and salary disbursements by the private sector, deflated by the Employment Cost Index, which is available only for the period 1980–1994.

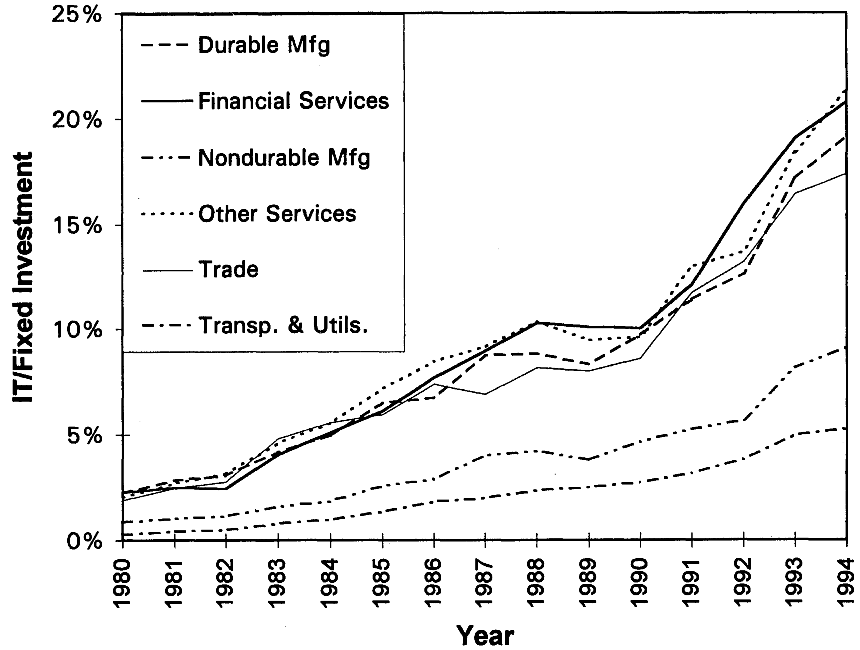
[2] The graphs in Figures 1–3 would be substantially flatter in later years if the quantities were measured in nominal terms (i.e., in current dollars).

Figure 2 **IT Investment per Employee in Different Industry Sectors (1990 Dollar Basis)**



IT refers to BEA asset category Office Computing and Computing Machinery. Source: BEA (1995) and Council of Economic Advisors (1995).

Figure 3 **IT as a Percentage of Annual Fixed Investment in Different Industry Sectors (1990 Dollar Basis)**



IT refers to BEA asset category Office Computing and Computing Machinery. Source: BEA (1995) and Council of Economic Advisors (1995).

demonstrate that the elasticity of substitution between capital and labor can be substantially different from unity, as assumed by the prevalent Cobb-Douglas production function. This has important implications for international trade and for the returns and factor shares of inputs. Later, more flexible production functions were developed, including the translog specification of Christensen et al. (1970) and the CES-translog introduced by Pollak et al. (1984). These flexible functional forms have been used to examine the degree of substitutability or complementarity between various inputs, including capital, labor, materials, and energy (see Berndt 1991 for a review). Our contribution to this line of research is to formally test whether IT is a net substitute or complement for the traditional inputs of ordinary capital and labor, and to examine the implications of our findings for the growth in IT intensity in different sectors of the economy.

The "productivity paradox" literature, surveyed by Brynjolfsson (1993) and Wilson (1993), generally failed to reject the null hypothesis of zero IT contribution. However, there is growing new evidence that IT investments in fact generate large positive returns. Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) analyze firm level data to show that IT investments generate returns that are often in excess of the returns on other types of investments. While these studies go a long way toward settling the debate on the productivity paradox, a number of questions regarding IT investments and productivity remain unanswered. For example, what types of firms and industries are in a better position to take advantage of the "information payoff," which is in part the focus of our study.

We use the same *Computerworld* survey data as Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) to jointly estimate output and substitution elasticities. Our analysis confirms earlier findings of positive marginal returns to IT investments. We also find evidence of excess returns on IT investments, more so relative to labor than with respect to ordinary capital. Our analysis suggests that IT capital is a net substitute for both ordinary capital and labor, in all sectors of the economy. One implication of this finding is that the slow improvements in labor productivity in many sectors of the economy may be due to the offsetting effects of growing IT capital but shrinking non-IT capital per worker. Combining the results on substitutability and excess returns of IT relative to labor implies that the economy could benefit from IT-labor substitution, examples of which are the increasingly frequent phenomena of IT-led restructuring and downsizing.

The rest of the paper is organized as follows. The next section sets up the production framework, defining the various elasticities to be estimated, and introduces alternative production functions. Section 3 describes the data and variable construction. The empirical results for the overall data and several data groupings are presented in §4. Finally, §5 offers some concluding remarks.

2. The Production Framework

We consider a production function of the form

$$V = f(C, K, L), \tag{1}$$

where the output is V = value added and the inputs are: C = IT Capital, K = Non-IT Capital, and L = Labor. All variables are measured in dollar terms, deflating current dollars into constant 1990 dollars with the use of suitable deflators. The output elasticity of IT Capital, $\eta_C = \partial \ln V / \partial \ln C$, represents the percentage increase in output due to a one percent increase in IT Capital. The marginal product f_C of IT Capital, which represents the increase in annual value added due to a one dollar increase in IT Capital stock, is given by $f_C = \eta_C \cdot (V/C)$. The output elasticities and marginal products of the other inputs are defined in an analogous manner.

Previous research by Brynjolfsson and Hitt (1995, 1996) and Lichtenberg (1995) has demonstrated that IT investments generate positive returns, i.e., $\eta_C > 0$. Lichtenberg further shows that IT capital investments generate *excess* returns relative to investments in ordinary capital. Following Lichtenberg (1995), we define excess returns statistics $x_{CK} = \eta_C - \eta_K \cdot (r_C/r_K) \cdot (C/K)$, for C relative to K and $x_{CL} = \eta_C - \eta_L \cdot r_C \cdot (C/L)$, for C relative to L, where r_i, $i = C, K$ is the ratio of rental price to purchase price of asset i.[3] We adopt Lau and

[3] In equilibrium, it must be true that $f_C/R_C = f_K/R_K = f_L/W_L$, where R_C and R_K are rental prices of IT Capital and Non-IT Capital, respectively, while W_L is the wage rate of labor. Thus, the excess returns to IT capital is $f_C - (R_C/R_K)f_K$ with respect to ordinary capital and $f_C - (R_C/W_L)f_L$ with respect to labor, which yields the excess return statistics above.

Tokutsu's (1992) estimates of $r_C = 0.42$ and $r_K = 0.07$.[4] We test for the presence of excess returns using our own model and data, by estimating the excess returns statistics x_{CK} and x_{CL}. The ability to take advantage of any excess returns on IT investments depends in part on the substitutability between IT and the other factors of production. A key objective of our analysis is to estimate and interpret substitution elasticities between IT capital and the other inputs.

Elasticity of Substitution

Originally introduced by Allen and Hicks (1934), the *Allen partial elasticity of substitution* (AES) has received much attention in the economics literature. The AES σ_{CK} between two inputs C and K, in the presence of a third input L, is given by

$$\sigma_{CK} = \frac{Cf_C + Kf_K + Lf_L}{C \cdot K} \cdot \frac{\bar{H}_{CK}}{\bar{H}}, \qquad (2)$$

where $f_C = \partial f / \partial C$ is the marginal product of IT Capital, $\bar{H}$ is the bordered Hessian determinant

$$\bar{H} = \begin{vmatrix} 0 & f_C & f_K & f_L \\ f_C & f_{CC} & f_{CK} & f_{CL} \\ f_K & f_{KC} & f_{KK} & f_{KL} \\ f_L & f_{LC} & f_{LK} & f_{LL} \end{vmatrix}, \qquad (3)$$

$f_{CK} = \partial^2 f / \partial C \partial K$ and $\bar{H}_{CK}$ is the cofactor associated with f_{CK} in the determinant $\bar{H}$. The remaining elements are analogously defined (see Appendix for more details).

The Allen elasticity is symmetric (i.e., $\sigma_{CK} = \sigma_{KC}$) and it measures the response of derived input demand to a price change of another input, holding output and all other input prices fixed. Further, the larger the magnitude of the substitution elasticity, the higher the degree of substitutability (if $\sigma_{CK} > 0$) or complementarity (if $\sigma_{CK} < 0$) between the two inputs. (The reader is referred to Chambers 1988 and Chung 1994 for textbook treatments of production functions and the properties of the Allen partial elasticity of substitution.) Of the three inputs considered in our analysis, IT Capital C clearly stands out in terms of the magnitude of price changes: the overall price decline of computing is 18.5% per year over our sample period. Hence, the interest in the substitutability of IT for the other inputs.

[4] $r_C = 0.42$ actually yields slightly conservative estimates of the excess returns statistics, given our definition of IT capital (see §3).

Production Functions

To estimate the Allen partial elasticities of substitution, we need to specify a functional form for the production function f. In this regard, the popular Cobb-Douglas production function is clearly not suitable since its functional form constrains the substitution elasticities to unity. The Constant Elasticity of Substitution (CES) production function, originally developed by Arrow et al. (1961) for two inputs and extended to more than two inputs by Uzawa (1962) and McFadden (1963), permits the substitution elasticities to be different from unity; however, it forces them to be equal for all pairs of inputs. This last feature is too restrictive if we expect that the substitutability between IT capital and ordinary capital is different from, say, that between IT capital and labor.[5]

There exist more flexible functional forms that impose fewer restrictions on the production function and substitution elasticities. A case in point is the translog production function (Christensen et al. 1970), which for the three inputs C, K, and L is characterized by the estimation equation (i and t index firm and year, respectively):

$$\begin{aligned} \log V_{it} = {} & \text{constants} + \alpha_C \log C_{it} + \alpha_K \log K_{it} \\ & + \alpha_L \log L_{it} + \beta_{CC}(\log C_{it})^2 + \beta_{KK}(\log K_{it})^2 \\ & + \beta_{LL}(\log L_{it})^2 + \beta_{CK}(\log C_{it})(\log K_{it}) \\ & + \beta_{CL}(\log C_{it})(\log L_{it}) \\ & + \beta_{KL}(\log K_{it})(\log L_{it}) + \epsilon_{it}, \end{aligned} \qquad (4)$$

where "constants" are the dummy terms that represent the effects of year and industry sector. The Cobb-Douglas production function is obtained from the translog as a special case when all the coefficients of the quadratic terms, β_{ij}, are set equal to zero. The translog may be considered a quadratic approximation to the "real" production function.

[5] In an earlier version of this paper, we analyzed a "CES-CD" production function in which a CES subaggregate of C and K is embedded in a Cobb-Douglas production function: $V = [\delta_C C^{-\rho} + \delta_K K^{-\rho}]^{-\alpha/\rho} L^{\beta}$. This specification is characterized by a constant value for σ_{CK} and might be useful for some empirical purposes. Here, however, we seek a production function that can be used to jointly estimate σ_{CK}, σ_{CL}, and σ_{KL}.

An even more flexible functional form than the translog is the CES-translog production function, suggested by Pollak et al. (1984). The CES-translog combines the CES and translog production functions and is given by the estimation equation:

$$\begin{aligned}\log V_{it} = {} & \text{constants} \\ & - \frac{1}{\rho}\log[\delta_C C_{it}^{-\rho} + \delta_K K_{it}^{-\rho} + (1 - \delta_C - \delta_K)L_{it}^{-\rho}] \\ & + \beta_{CC}(\log C_{it})^2 + \beta_{KK}(\log K_{it})^2 \\ & + \beta_{LL}(\log L_{it})^2 + \beta_{CK}(\log C_{it})(\log K_{it}) \\ & + \beta_{CL}(\log C_{it})(\log L_{it}) \\ & + \beta_{KL}(\log K_{it})(\log L_{it}) + \epsilon_{it}, \qquad (5)\end{aligned}$$

where $0 \leq \delta_C, \delta_K \leq 1$. The CES-translog includes the CES, translog and Cobb-Douglas production functions as special cases. In particular, when all the quadratic terms are zero we obtain the CES production function, while the translog production function is obtained in the limit as $\rho \to 0$. These nested properties enable tests of model specification using conventional procedures. Pollak et al. (1984) estimate the dual CES-translog cost function on eight different data sets and find that the CES-translog outperforms both the CES and translog cost functions under a standard modelling scenario. Our approach employs the CES-translog *production* function rather than the dual *cost* function, as in the Pollak study.

In §4, we conduct our own model specification tests, comparing the CES-translog to the nested Cobb-Douglas, CES and translog production functions. Unlike the Cobb-Douglas and CES production functions, which are characterized by a constant value for the output and substitution elasticities, respectively, the translog and CES-translog production functions do not give a constant value for either type of elasticity. We evaluate the elasticities at the medians of the exogenous variables, V, C, K, and L, applying the equations shown in the Appendix. Since the substitution elasticities are highly nonlinear in the model parameters, we approximate the means and standard errors of the elasticity estimates using a Monte Carlo simulation method, as in Anderson and Thursby (1986) and Krinsky and Robb (1990). We first generate random numbers from a joint distribution of model parameters, which is an asymptotic multivariate normal distribution. Then, we evaluate the elasticity equations using the drawn random numbers. The empirical results reported in §4 are based on 3,000 drawings of random numbers.[6] We follow the standard practice of evaluating the elasticities for representative (mean or median) values of the exogenous variables, as in Berndt and Wood (1975, 1979), Griffin and Gregory (1976), Pollak et al. (1984), Anderson and Thursby (1986), and Krinsky and Robb (1990), among others. We evaluate the elasticities at the median values of exogenous variables to minimize the effect of a few extreme values in our noisy survey data set. In this way, we estimate output and substitution elasticities and excess returns statistics for the overall data sample and for several sample splits based on various firm characteristics.

3. Data and Variables

The construction of variables in this study closely follows that of Brynjolfsson and Hitt (1995). Therefore, we provide only a brief description here and refer the reader to the previous study for further details. Our source for IT-related data is the IDG/*Computerworld* surveys of IS spending by large U.S. corporations, conducted annually during the period 1988 to 1992.[7] This survey focuses primarily on large Fortune 500 firms; about two-thirds of the firms are from the manufacturing sector, while the remaining are mainly service firms. As the surveyed firms are all publicly traded, we are able to augment the IT-related data with matching data on sales, capital investments, labor expenses, and operating income, from Compustat.[8] The input and output variables are measured in dollar terms, converting nominal figures to constant 1990 dollars using suitable deflators.

[6] We did not consider random numbers which led to substitution elasticities outside the range of ± 10.

[7] Over the sample period, these survey data were used to compile *Computerworld's* annual *Premier 100* ranking of the 100 most productive users of IT.

[8] As in the *Premier 100* reports of *Computerworld*, survey data for a given year are matched with Compustat data for the previous fiscal year. Thus, for example, survey data from 1990 are matched with Compustat data for fiscal year 1989.

IT Capital C is constructed from the IDG survey data by aggregating computer capital and a capitalized value of IS labor expenses. Inclusion of the latter in a measure of IT Capital is justified to the extent that a large fraction of IS labor expenses is typically allocated to the development of software, a capital good. Computer capital is calculated by adding the market value of central processors to the total value of desktop machines. The latter is taken to be equal to the number of PCs and terminals multiplied by Brynjolffson and Hitt's estimate of \$2,835 for the average value in 1990 of one desktop machine. The current value of computer capital is deflated using the computer deflator of Gordon (1991), extrapolated through 1992 at a constant rate. Annual IS labor expense is calculated from the IDG survey data as the total MIS budget multiplied by the fraction of the budget spent on IS staff, deflated using the Index of Total Compensation Cost (private sector) (Council of Economic Advisors 1995). Following Brynjolfsson and Hitt (1995), the net capital stock created by IS labor expenses is estimated to be equal to three times the current IS labor expense.[9] Thus, IT Capital C is equal to deflated computer capital plus three times the deflated annual IS labor expenses.

Non-IT Capital K is obtained by subtracting the value of computer capital (calculated above) from the total net capital stock for the firm. The net capital stock is constructed along the lines of Hall (1990), as the inflation-adjusted sum of: the net value of plant; value of the firm's inventories; value of investments in unconsolidated subsidiaries; and intangibles. The plant value is adjusted for inflation by multiplying the net book plant value by the ratio of the GDP deflator for fixed nonresidential investment (Council of Economic Advisors 1995) in the base year (1990) to GDP deflator AA years ago. AA is the average age of plant, which is calculated as the ratio of total accumulated depreciation (gross plant minus net plant) and the current year depreciation.

Labor Expenses L is measured net of IS labor expenses (to avoid double counting of IS labor). For roughly a third of the firms in the sample, total labor costs are available directly from Compustat (item number A42). For the remaining firms, labor costs are estimated to be equal to the industry average labor cost per employee multiplied by the total number of employees. In either case, Labor L is calculated as total labor cost minus IS labor expense, deflated by the Index of Total Compensation Cost (private sector) (Council of Economic Advisors 1995).

Finally, output is measured by the annual value added for the firm. We select value added (i.e., net output) as opposed to sales (i.e., gross output), as the former measure is less noisy and more comparable across industry sectors. Value added is defined as deflated Sales less deflated Materials. Annual sales for a firm is obtained from Compustat and deflated using industry-specific output implicit price deflators (BEA 1994). Materials is calculated by subtracting labor expenses (calculated above) from total expenses (sales minus the operating income before depreciation) and deflating the resulting value using the Producer Price Index for Intermediate Materials, Supplies and Components (Council of Economic Advisors 1995).

There are a number of data problems, as explained in detail by Brynjolfsson and Hitt (1995, 1996), and summarized here. First, the *Computerworld* survey excludes

Table 1 **Sample Summary Statistics Using 1990 Dollar Basis (Dollar Figures in Millions)**

Variable	Average Per Firm	Fraction of Value Added: Mean	Fraction of Value Added: St. Dev.
IT Capital, C	337.96	0.117	0.135
Non-IT Capital, K	6,443.8	2.00	1.76
Labor Expense, L	1,731.4	0.612	0.351
Value Added, V	3,158.8	1.0	–
Sales, Q	8,596.8	3.15	3.82
Employees	52,819	–	–
N		1,131	

[9] In our estimation of excess returns statistics, we apply Lau and Tokutsu's (1992) estimate of $r_C = 0.42$—for the ratio of rental to purchase price of computer capital—to both components of our IT Capital measure. This is consistent with the following assumptions (see Lichtenberg 1995 for details): 7% nominal annual interest rate, 20% depreciation rate and 15% price decline for computer capital, and 33% depreciation (i.e., 3-year service life) and 2% price decline for the capitalized value of IS labor expenses. To the extent that the unit cost of IS labor has remained constant or increased slightly in real terms, our assumptions lead to somewhat conservative estimates of the excess returns statistics.

Table 2 **Trends Over Time (1990 Dollar Basis): Average Firm Size, Input Deflators and the Ratios C/K, C/L, and C/V, for Each Year in the Sample Period 1988–92 (Dollar Figures in Millions)**

Variable	1988	1989	1990	1991	1992
V	4,713	4,573	2,898	2,698	2,541
Employees	78,523	71,498	49,531	44,743	44,212
P_C	81.5	66.42	54.13	44.12	35.96
P_K	103.2	105.9	108.2	109.0	108.6
P_L	97.6	102.3	107.0	111.7	115.6
C/K	0.045	0.056	0.069	0.088	0.103
C/L	0.113	0.155	0.195	0.262	0.287
C/V	0.062	0.078	0.096	0.131	0.163
N	132	133	267	295	304

some IT assets, notably software and communications equipment. Thus, the IT variable is somewhat narrow and the results should be cautiously interpreted. Second, the survey is biased toward the largest manufacturing firms in the economy, despite the fact that the service sector accounts for three quarters of the U.S. GDP (Quinn and Bailey 1994). Third, the survey data is self-reported and therefore it is inevitably noisy. Due to the speedy obsolescence of computer equipment, there is some question as to whether managers are able to accurately estimate the market value of computers. Finally, the measurement of output, especially for service firms, is imprecise due to the fact that the adopted quantitative measures do not fully account for such qualitative factors as quality and variety of the product or service (see e.g., Quinn and Bailey 1994). This measurement problem is somewhat alleviated by our use of firm level data as opposed to aggregate industry or sector-level data. On balance, this data set is probably the best available at the firm level.

Table 1 presents some summary statistics on the variables, in constant 1990 dollars. The average firm is quite large, with annual sales and value added of \$8.6 billion and \$3.2 billion, respectively, and employment over 50,000. The size distribution is skewed to the right: for example, the mean of the sales distribution is only slightly smaller than the third quartile. On average, IT Capital constitutes 11.7% of annual value added. By comparison, the stock of non-IT capital is twice the magnitude of annual value added for the average firm. Finally, labor expenses comprise 61% of value added. The overall data set has a number of outliers, undoubtedly reflecting measurement and reporting errors in the survey data. To mitigate the bias due to these data errors, we eliminate a total of 83 observations (mostly from Financial Services and Transport and Utilities) with extreme, even negative, values for key variables, leaving a balance of 1,131 observations for the overall sample.[10]

Table 2 presents the trends in some of the variables over our sample period 1988–92. Starting in 1990, note that the number of observations in each year more than doubles and the average firm size drops sharply. Perhaps the scope of the *Computerworld* survey was broadened in 1990 to include a number of smaller firms relative to previous years. The computer deflator P_C (applied to the "hardware" component of IT Capital) declines at the annual rate of 18.5% while the deflators for ordinary capital and labor, P_K and P_L, increase over the sample period. IT Capital as a percentage of Non-IT Capital, C/K, more than doubles over the interval, increasing from 4.5% to 10.3%. The ratios C/L and C/V go up even more over the sample period. Thus, there is clear evidence of the substitution of IT for both ordinary capital and labor, in response to the relative price trends. In the following section, we conduct a detailed analysis of IT substitutability for the overall data set and for several meaningful sample splits.

[10] Our criteria for removal of outliers is to eliminate all observations in the 1% and 99% tails of the distributions of the input ratios C/V, K/V, L/V, and C/K.

4. Empirical Results

4.1. Analysis of Full Sample

We start by comparing the CES-translog specification to its special cases: the CES, translog, and Cobb-Douglas production functions. Tables 3 and 4 present parameter and elasticity estimates, respectively, using the CES-translog and translog production functions. The CES-translog and translog parameters were estimated using nonlinear least squares and ordinary least squares regressions, respectively. For the CES-translog production function, ρ and δ_K are significant ($p < 0.05$), while δ_C is only weakly significant ($p < 0.16$). The coefficients of the quadratic terms, β_{ij}, are not *individually* significant, but they are *jointly* significant: the null hypothesis H_0: $\beta_{ij} = 0$ (for $i, j = C, K, L$) is rejected with $p < 0.01$. Accordingly, the CES production function is rejected in favor of the CES-translog.

The translog production function is also rejected in favor of the CES-translog specification: the null hypothesis H_0: $\rho = 0$ is rejected with $p < 0.01$. (Recall that the CES-translog reduces to the translog when $\rho = 0$.) Further, the standard regularity conditions of quasi-concavity and non-negative marginal products (see equations in the appendix) are violated for 89% of the observations using the translog production function, while the violations are virtually zero under the CES-translog. We conclude that the CES-translog production function dominates the translog for our data sample. Accordingly, our empirical analysis in the sequel is based on the CES-translog production function.

Table 3 Parameter Estimates from the CES-Translog and Translog Specifications

	CES-Translog		Translog	
Parameter	Mean	S.E.	Mean	S.E.
Intercept	0.71	0.183	2.16	0.268
ρ	0.11	0.009	–	–
δ_C	0.12	0.083	–	–
δ_K	0.22	0.089	–	–
α_C	–	–	0.46	0.078
α_K	–	–	−0.30	0.087
α_L	–	–	0.54	0.078
β_{CC}	0.002	0.014	0.042	0.011
β_{KK}	0.007	0.010	0.103	0.011
β_{LL}	−0.0001	0.016	0.098	0.014
β_{CK}	−0.0002	0.020	−0.052	0.018
β_{CL}	−0.008	0.023	−0.056	0.019
β_{KL}	−0.003	0.020	−0.120	0.017
N		1131		

Note: The estimates of year and industry sector dummy coefficients are omitted for the sake of brevity.

Table 4 Estimated Mean and Standard Errors for the Elasticities, Evaluated at the Sample Median, Using a Monte Carlo Simulation of 3,000 Drawings

	CES-Translog		Translog	
Elasticity	Mean	S.E.	Mean	S.E.
η_C	0.104	0.020	0.068	0.014
η_K	0.281	0.021	0.263	0.012
η_L	0.601	0.061	0.658	0.017
χ_{CK}	0.021	0.019	−0.010	0.016
χ_{CL}	0.068	0.018	0.029	0.015
σ_{CK}	1.006	0.909	−5.124	4.911
σ_{CL}	1.063	0.526	0.925	2.743
σ_{KL}	1.005	0.118	4.853	2.645

The output elasticity of IT capital, η_C, is estimated to be 0.104 for the median firm; it is significantly different from zero ($p < 0.001$). This estimate is virtually identical to Brynjolfsson and Hitt's (1995) estimate of $\eta_C = 0.109$, using the Cobb-Douglas sector effects model, despite small differences in our construction of variables. Lichtenberg's (1995) estimate of IT elasticity is 0.11, although he does not include capitalized labor expenses in his measure of IT Capital. The implied gross marginal product is 117% for the median firm.[11] If this number seems very high, note the following. First, there is substantial dispersion in our estimation of gross return: the inter-quartile range on the estimate of gross marginal product is 116.3%. Second, the marginal product is gross of firm effects, which in Brynjolffson and Hitt's analysis, reduce the gross marginal product from 117% to 53%.[12] Finally, the marginal product is gross of de-

[11] Again, our estimate of gross marginal product of IT is virtually identical to the value implied by Brynjolfsson and Hitt's (1995) Cobb-Douglas sector effects model.

[12] Since the CES-translog model is nonlinear, the simple "within transform" used by Brynjolfsson and Hitt (1995) does not remove firm effects from our estimation.

preciation. According to Lau and Tokutsu (1992) the average annual depreciation rate of computer capital over the period 1960–90 is 20%. Examining the excess return statistics for the representative (median) firm, we find evidence of excess returns on IT capital relative to labor and weaker evidence of excess returns on IT capital relative to ordinary capital.

Turning to the substitution elasticity estimates, we find that the means for all three elasticities are slightly greater than unity. One-tailed tests suggest, with varying degrees of confidence, that all three inputs are pairwise substitutable ($p < 0.15$ for $\sigma_{CK} > 0$, $p < 0.05$ for $\sigma_{CL} > 0$, and $p < 0.001$ for $\sigma_{KL} > 0$). In other words, we find that IT capital is a *net* (or long-run) substitute for both ordinary capital and labor. It should be noted that our data sample is basically cross sectional, and differences among cross sectional units are more likely to reflect long run or equilibrium patterns, as compared to time series, that are sensitive to cyclical trends (see e.g., Griliches 1967, Osterman 1986). Capital-labor substitution has been extensively studied in the production economics literature using a variety of models and data sets. Interestingly, Berndt (1991, p. 454–455) reports that a substantial part of the empirical evidence from studies using cross sectional data cannot reject the null hypothesis that the elasticity of substitution between labor and capital is equal to unity. (Our estimate of $\sigma_{KL} = 1.005$.) Thus, our findings concur with the existing literature on capital-labor substitution, increasing the level of confidence in our model and estimation methods.

Our results are relevant to the debate on the Solow paradox, which is that "we see computers everywhere except in the productivity statistics" (Solow 1987). For example, Quinn and Bailey (1994) report that over the period 1973–1989 the average annual growth in labor productivity (measured as gross product originating per labor hour) for the U.S. business sector has been a mere 1.08 percent. In explaining this apparent paradox, Brynjolfsson (1993) and Oliner and Sichel (1994) have noted that computers are not "everywhere," and computer equipment still accounts for a relatively small fraction (2 to 5 percent) of the overall capital stock. Our results complement this explanation by further suggesting that, *ceteris paribus*, improvements in labor productivity due to the accumulation of more IT capital per worker over time is offset by the shrinking levels of ordinary capital per worker.[13] Thus, not only is the stock of computer capital in the economy still relatively small, but the impact of IT adoption on labor productivity is partially neutralized by the displacement of ordinary capital. Based on our empirical results, the confluence of excess returns and IT substitutability will spur greater levels of IT investments throughout the economy. Our finding that IT is a net substitute for ordinary capital and labor suggests that the factor shares of IT in production will grow to more significant levels over time. Indeed, Figures 2 and 3 depict increasing new IT investment intensities across all industry sectors. If the recent rash of IT-led restructuring and downsizing (e.g., Roach 1991, *Economist* 1995) heralds the beginning of a new trend, then a measurable impact of IT on output and productivity statistics might be witnessed sooner than otherwise expected.

4.2. Analysis of Sample Splits

In this subsection, we conduct an analysis of the following data groupings: (i) *Sector*: Manufacturing vs. Service, (ii) *IT Intensity*: High vs. Low factor share of IT Capital, and (iii) *Growth Options*: High vs. Low growth options, as measured by the ratio of book value of assets to firm value. This sample-split analysis is along the lines of Brynjolfsson and Hitt (1995), who estimate output elasticities for data groupings based on sector, growth (defined in terms of annual sales growth rate), and measurability of output. Table 5 presents summary statistics on our data groupings, and the results are summarized in Table 6.

As explained in §2, we follow the standard practice (Anderson and Thursby 1986, Krinsky and Robb 1990) of evaluating the elasticities at the median values of the exogenous variables, using a Monte Carlo simulation to approximate the means and standard errors.[14] In broad terms, all output elasticities are significantly different from zero, as is the excess returns statistic x_{CL} across most data groupings. x_{CK} is generally indistinguishable from 0. The mean values of all substitution elasticities are positive, though the estimates are not different from zero at

[13] We thank the guest associate editor for suggesting this point.

[14] When we also allow for cross-sectional variation the estimated standard errors are slightly higher, but the results are not qualitatively different.

Table 5 Sample Split Characteristics (1990 Dollar Basis): Annual Value Added, Employment, and Inputs as a Fraction of Value Added for Various Data Groupings (Dollar Figures in Millions)

		V	Employees	C/V	K/V	L/V	N
Sector	Manufacturing	3,200	46,347	0.104	1.86	0.60	773
	Service	3,230	71,662	0.148	2.32	0.65	328
IT Intensity	High	3,280	51,237	0.171	2.11	0.59	554
	Low	3,093	55,336	0.059	1.89	0.64	566
Growth Options	High	2,736	47,065	0.112	1.80	0.60	545
	Low	3,611	59,227	0.116	2.18	0.62	575

the usual significance levels. However, there is mixed statistical evidence for the subsamples that IT capital is a net substitute for labor and ordinary capital, with p values ranging from 0.09 to 0.44 across the various data groupings. Although the differences in elasticities across subsamples are not significant at the usual significance levels, it is still possible to gain qualitative insights; we discuss the results for each grouping in turn.

Manufacturing vs. Service

This is a natural grouping of the data, and it is pervasive in the productivity and economic competitiveness literatures (see e.g., Roach 1991, Brynjolsson 1993, Quinn and Bailey 1994, and *Economist* 1995). The available empirical evidence suggests that although the service sector is more IT intensive, it is lagging manufacturing in terms of productivity growth. For example, Quinn and Bailey report that the average annual growth in labor productivity, measured in gross product originating (GPO) per hour of labor input, over the period 1973–1989, has been 1.71% in manufacturing and only 0.74% in the service producing sector. The gap has widened in the 1990s: annual growth in labor productivity has

Table 6 Analysis of Sample Splits Using the CES-Translog Specification

	Sector		IT Intensity		Growth	
	Manufacturing	Service	High	Low	High	Low
η_C	0.09	0.10	0.19	0.09	0.09	0.10
	(0.02)	(0.06)	(0.06)	(0.03)	(0.02)	(0.03)
η_K	0.33	0.17	0.27	0.29	0.31	0.28
	(0.02)	(0.05)	(0.03)	(0.02)	(0.03)	(0.03)
η_L	0.58	0.68	0.54	0.65	0.60	0.60
	(0.07)	(0.15)	(0.07)	(0.11)	(0.09)	(0.08)
χ_{CK}	0.00	0.05	0.04	0.04	−0.01	0.03
	(0.02)	(0.05)	(0.06)	(0.03)	(0.02)	(0.03)
χ_{CL}	0.06	0.05	0.13	0.07	0.05	0.06
	(0.02)	(0.05)	(0.05)	(0.03)	(0.02)	(0.03)
σ_{CK}	0.93	0.51	0.86	0.58	1.18	0.99
	(1.02)	(3.32)	(1.44)	(2.02)	(1.95)	(1.31)
σ_{CL}	1.35	0.91	0.97	0.88	1.40	0.95
	(1.01)	(1.30)	(1.10)	(2.67)	(1.58)	(0.81)
σ_{KL}	1.02	1.10	1.07	1.04	1.01	1.03
	(0.13)	(0.80)	(0.29)	(0.29)	(0.19)	(0.18)

Note: Means and standard errors are estimated at the sample median using a Monte Carlo simulation of 3,000 drawings.

reached nearly 5% in manufacturing, compared to 2% for the economy as a whole (*Economist* 1995).

Over two-thirds of the firms in our sample are from manufacturing, while the remaining are mostly service firms. The average annual value added per firm is roughly the same for the two sectors. The average service firm has a higher IT intensity than its manufacturing counterpart and it uses relatively greater proportions of other inputs as well. This might either reflect lower average multifactor productivity in the service sector, or may be an artifact of systematic mismeasurement of output for service firms. Our estimates of IT output elasticity for the two sectors are 0.09 for manufacturing and 0.10 for service. Note that the values are close to each other and to the overall average for the data set. Brynjolfsson and Hitt (1995) also could not reject the null hypothesis that the IT elasticities are equal in the two sectors. Our estimates of the excess returns statistics suggest that the average manufacturing firm enjoys excess returns in IT relative to labor. All other excess return statistics are indistinguishable from zero. The elasticity of substitution σ_{CK} is estimated to be 0.93 for manufacturing and 0.51 for service. The σ_{CL} estimates are 1.35 for manufacturing and 0.91 for service. Overall, these numbers suggest that the manufacturing sector is relatively better positioned to take advantage of IT improvements.

The substitution of IT for other inputs is perhaps most dramatic in the form of "downsizing" or "restructuring." The turn around of the car industry in the 1990s can largely be attributed to the transformation of production techniques and slimmer workforces brought about by the application of information technologies (*Economist* 1995). According to Roach (1991), "increased productivity [in manufacturing] has been synonymous with labor saving," and "after years of massive investments in technology, service companies employ just as many workers as before." These observations by Roach are echoed in our findings that the manufacturing sector on average has greater excess returns on IT investments and higher substitutability of IT for other factors, as compared to the service sector. This provides an explanation for why manufacturing appears to have had greater success with IT-led restructuring than service. Whether the recent rash of white collar layoffs are signs of change remains to be seen.

IT Intensity

Here, we separate firms into two subsamples based on IT intensity, measured by the factor share of IT capital among the inputs to production. This is to be distinguished from the dependent variable in studies such as Gremillion (1984) and Harris and Katz (1991) where "IT intensity" or "system-intensiveness" is defined as the ratio of annual IS *expenses* to total expenses or sales. We believe that IT capital stock is a more complete indicator of the firm's production technology than annual IS expenses. Examining the summary statistics in Table 5, the average firm in the low IT intensity subsample is less capital intensive, but more labor intensive, than its counterpart in the high IT intensity group.

As reported in Table 6, the high IT intensity subsample has a higher average IT output elasticity than the low IT intensity subsample. The difference in IT elasticities (0.19 vs. 0.09) is statistically significant at the 10% significance level. However, the marginal product of IT capital is higher for the median low IT intensity firm, due to its lower value for the IT input ratio C/V, possibly reflecting an underinvestment in IT. Both groups have excess returns in IT relative to labor, but not with respect to ordinary capital. To the extent that higher IT substitutability facilitates growth in IT intensity, one would expect that the high IT intensity subsample would be characterized by higher IT substitution elasticities. This is not borne out by our findings: the differences in elasticity estimates are not statistically significant. Perhaps the firms with currently high IT intensity have already incorporated information processing in their business processes, leaving little room for further automation. The combination of excess returns and IT-labor substitutability for both groups suggests the possibility for a leveling of the "technological playing field" in the future.

Growth Options

It is widely believed that IT infrastructure is a key resource that enables firm growth (Weill 1993, Kambil et al. 1993). Previous research has examined the relationship between firm growth and IT investment. One might expect that firms enjoying revenue growth would have free cash available to invest in IT, while firms that are not growing would cut back on IT spending. The available empirical evidence, however, suggests that many types of IT investments are relatively "inelastic" to the current financial performance of the firm (Sobol 1993). Brynjolfsson and Hitt (1995) find that firms that are not growing actually have higher marginal returns on IT, which they point out does not support the hypothesis that IT gets a disproportionate share of new spending. According to Mead (1990), IT investments are driven by competitive challenges rather than current economic difficulties.

Thus, current economic performance is only weakly correlated with IT investment. We believe that a growth characteristic that might better reflect the underlying production technology and IT investment strategy is the degree of growth *options* in the firm's investment opportunity set. Firms with more growth options have fewer "assets in place" and relatively greater access to positive net present value projects. On the other hand, a regulated public utility or mining company might have most of its assets in place and relatively little by way of growth options. We borrow Smith and Watt's (1992) proxy measure of growth options, as being inversely related to the ratio of book value of assets to firm value.[15] In other words, this measure of growth options is roughly the inverse of the well known Tobin's *Q* (see e.g., Berndt 1991).

Examining the summary statistics in Table 5, we find that firms with high growth options are smaller in size (both in terms of annual value added and employment) and have a substantially lower capital intensity, as compared to firms with more of their assets in place. However, the two groups appear to be comparable in terms of IT intensity. Examining the results in Table 6, the subsamples corresponding to high and low growth options have similar estimates for all elasticities, though the IT-substitution elasticities appear to be higher for the representative high growth firm. This might be due to the fact that high growth firms have less free cash flow (Smith and Watts 1992) and can therefore build their IT infrastructure only at the expense of the other inputs, i.e., by factor substitution in favor of IT. Also, to the extent that firms with high growth options, by their very nature, tend to seek out profitable investment opportunities, they are also likely to be more responsive to the economic opportunities presented by the price/performance improvements in IT.

5. Concluding Remarks

The rapid improvements in IT are creating valuable economic opportunities, that can be availed in part by the substitution of IT for other factors of production. This type of substitution is in fact occurring throughout the economy, as evidenced by the growing share of IT in new fixed investments and by the increasing levels of new IT investments per employee (Figures 1–3). Lau and Tokutsu (1992) estimate that if the growth of computer capital since 1960 were replaced by a comparable accumulation of noncomputer capital, then "the rate of growth of U.S. aggregate real output would have been reduced by approximately 1.2% per annum." This gives a sense of the aggregate economic value of IT substitution.

A key result that has emerged from our analysis is that IT capital is a net substitute for ordinary capital and labor in all sectors of the economy. This suggests that the slow improvements in labor productivity might be due to the offsetting effects of more IT capital and less non-IT capital per worker. We find evidence of excess returns on IT investments relative to labor. This combined with the substitutability of IT for labor provides an economic rationale for IT-led restructuring and downsizing which often, though not always, have the net effect of replacing labor input with IT. The qualitative nature of our results are shown to apply to a variety of data groupings, based on industry sector (manufacturing vs. service), high or low IT intensity, and high or low degree of growth options.

On a technical note, we have a message for researchers in the area of IT and productivity. We estimated a CES-translog production function and showed that it dominates the nested special cases of the Cobb-Douglas, CES, and translog production functions. The majority of the literature on IT productivity is based on the use of the Cobb-Douglas production, and to a lesser extent the translog production function. Our analysis suggests that the estimation of output elasticity is quite robust to model specification, and we got comparable estimates

[15] Smith and Watts (1992) find that growth options in firms' investment opportunity set is an important variable in explaining cross sectional variation in financing, dividend, and compensation policies.

for output elasticities using a variety of models. Further, our estimates of output elasticities are close to the estimates obtained by earlier research using the same data set. For the overall sample, our estimates of all three substitution elasticities are close to unity, suggesting that the widely used Cobb-Douglas production function is a reasonable model for purposes of estimating output elasticities and returns on investments.

It is important to point out some of the limitations of our analysis. First, our production model includes only three input variables and in many ways over-simplifies the richness inherent in production technologies. In all our estimations, however, our input variables and industry and year dummies "explained" over 95 percent of the total variation in the output variable. Second, we do not account for firm effects. One way to account for firm effects is through the use of the "within transform" (Brynjolfsson and Hitt 1995), but this does not remove firm effects in our nonlinear model. Our use of industry dummies and disaggregate analyses of a variety of data groupings to some extent controls for the heterogeneity in our data sample. Third, due to the short time period of the data, we are unable to include a sophisticated lag structure to control for autocorrelation. Alternatively, we estimated our model for two groups, separating data for the first, third and fifth years from data for the second and fourth years.[16] The results for the two groups are not substantially different from the aggregate sample, and therefore autocorrelation does not appear to be a serious problem. In any case, autocorrelation only lowers the efficiency of the estimates and does not affect their consistency. Finally, as pointed out in §3, there are a number of data problems. It should be noted, however, that this is the most current and comprehensive data set available at the firm level.

In terms of future research, it would be interesting to estimate the CES-translog model using aggregate data at the economy or industry sector level, for which price data might also be available. In that case it would be possible to estimate the dual cost function and identify factors affecting the derived demand for IT and other input factors. It would also be interesting to analyze international data to see if systematic differences in IT productivity and substitutability affect the adoption and diffusion of new technologies. At a more micro level, it would be worthwhile to examine the technology strategies of specific firms or industries to enhance our understanding of the mechanism by which IT substitution affects business processes.

Another interesting direction for future research would be to analyze time series data and try to separate the effects of factor substitution and technical change. While examples abound of the former, and some are listed in the introduction, there is limited evidence of technical change induced by the adoption of IT. For example, Krueger (1993) reports that the proportion of workers using computers at work rose from 24.6% in 1984 to 37.4% in 1989, and computer users enjoy a wage premium of 10–15%. This segment of workers is clearly an outlier from the overall trend in labor productivity and probably are an outcome of discontinuous technical change rather than gradual factor substitution. In any case, the type of analysis in this paper, as well as standard growth accounting exercises, are unable to separate the above two effects. As pointed out by Tripplet (1994), if factor substitution has dominated technical change, leading to cost savings but leaving the production function essentially unchanged, then this is a possible explanation for the Solow paradox. Whether or not such an explanation accurately describes the role of IT in economic production would be an important area for further research.

In closing, we raise a public policy issue which has a bearing on our ability to fully exploit improvements in IT. Given the potentially large payoffs from IT, it may be worthwhile at the economy level to lower any "barriers" to IT adoption (see, e.g., Parente and Prescott 1994). One such barrier is created by the externality effects associated with IT investments. For example, the cost savings generated by the substitution of cheaper IT for more expensive non-IT inputs are not fully retained by the firms making the investments. A large fraction of the savings are passed down the value chain, ultimately to the end users, due to competition in the product markets. This tends to decrease the incentives to invest in IT for the firm in question. One way to internalize these externalities might be through tax incentives associated with investments in information technology assets. Whether or not such a scheme should be

[16] We are grateful to one of the reviewers for suggesting this approach.

implemented is a political question. That IT investments will continue to grow in size and importance is beyond question.[17]

[17] We would like to sincerely thank the associate editor, three anonymous reviewers, and the participants of WISE'94 for their helpful comments and suggestions. We are also grateful to International Data Group, *Computerworld*, and especially Mr. Paul Gillin for providing the survey data used in this study.

Appendix: CES-Translog Elasticity Equations

In this appendix, we provide the detailed equations that are used in calculating the Allen partial elasticities of substitution, defined by Equation (2), for the CES-translog production function. The first and second order derivatives of the production function, used in calculating the bordered Hessian $\bar{H}$ in Equation (3) are given by:

$$f_C = V\cdot\left[\frac{\delta_C C^{-\rho-1}}{Z} + \frac{\beta_{CK}}{C}\log K + \frac{\beta_{CL}}{C}\log L + \frac{2\beta_{CC}}{C}\log C\right],$$

$$f_K = V\cdot\left[\frac{\delta_K K^{-\rho-1}}{Z} + \frac{\beta_{CK}}{K}\log C + \frac{\beta_{KL}}{K}\log L + \frac{2\beta_{KK}}{K}\log K\right],$$

$$f_L = V\cdot\left[\frac{\delta_L L^{-\rho-1}}{Z} + \frac{\beta_{CL}}{L}\log C + \frac{\beta_{KL}}{L}\log K + \frac{2\beta_{LL}}{L}\log L\right],$$

$$f_{CC} = \frac{f_C^2}{V} - \frac{f_C}{C} + V\cdot\left[\frac{-\rho\delta_C C^{-\rho-2}}{Z} + \frac{\delta_C^2 C^{-2\rho-2}\rho}{Z^2} + \frac{2\beta_{CC}}{C^2}\right],$$

$$f_{KK} = \frac{f_K^2}{V} - \frac{f_K}{K} + V\cdot\left[\frac{-\rho\delta_K K^{-\rho-2}}{Z} + \frac{\delta_K^2 K^{-2\rho-2}\rho}{Z^2} + \frac{2\beta_{KK}}{K^2}\right],$$

$$f_{LL} = \frac{f_L^2}{V} - \frac{f_L}{L} + V\cdot\left[\frac{-\rho\delta_L L^{-\rho-2}}{Z} + \frac{\delta_L^2 L^{-2\rho-2}\rho}{Z^2} + \frac{2\beta_{LL}}{L^2}\right],$$

$$f_{CK} = \frac{f_C f_K}{V} + V\cdot\left[\frac{\rho\delta_C\delta_K C^{-\rho-1}K^{-\rho-1}}{Z^2} + \frac{\beta_{CK}}{CK}\right],$$

$$f_{CL} = \frac{f_C f_L}{V} + V\cdot\left[\frac{\rho\delta_C\delta_L C^{-\rho-1}L^{-\rho-1}}{Z^2} + \frac{\beta_{CL}}{CL}\right],$$

$$f_{KL} = \frac{f_K f_L}{V} + V\cdot\left[\frac{\rho\delta_K\delta_L K^{-\rho-1}L^{-\rho-1}}{Z^2} + \frac{\beta_{KL}}{KL}\right],$$

where $Z = \delta_C C^{-\rho} + \delta_K K^{-\rho} + \delta_L L^{-\rho}$ and $\delta_L = 1 - \delta_C - \delta_K$. In Equation (2), $\bar{H}_{CK}$ is the cofactor associated with f_{CK} in the determinant $\bar{H}$. The regularity condition of non-negative marginal products requires that $f_C \geq 0$, $f_K \geq 0$, and $f_L \geq 0$. And, the regularity condition of quasiconcavity requires that the bordered Hessian of Equation (3) be positive semidefinite, which implies the following inequalities:

$$\begin{vmatrix} 0 & f_C \\ f_C & f_{CC} \end{vmatrix} \leq 0, \quad \begin{vmatrix} 0 & f_C & f_K \\ f_C & f_{CC} & f_{CK} \\ f_K & f_{KC} & f_{KK} \end{vmatrix} \geq 0, \quad \begin{vmatrix} 0 & f_C & f_K & f_L \\ f_C & f_{CC} & f_{CK} & f_{CL} \\ f_K & f_{KC} & f_{KK} & f_{KL} \\ f_L & f_{LC} & f_{LK} & f_{LL} \end{vmatrix} \leq 0.$$

Needless to say, the elasticities are highly nonlinear in the model parameters. For this reason, we use Monte Carlo simulation to estimate the elasticities, as explained in §2.

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