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Substitutability and Accumulation of Information Technology Capital in U.S. Industries

Hyunbae Chun* and Sung-Bae Mun†

The substitution toward information technology (IT) capital fueled by the rapid decline in IT prices is regarded as an important source of U.S. economic growth. Using data on 41 U.S. industries for the period from 1984 to 1999, this article examines the degree of substitutability between IT capital and other inputs and quantifies the contribution of IT substitution to the accumulation of IT capital per hour worked. Estimates of various elasticities of substitution indicate that IT capital and other factors of production are substitutes. In particular, the substitution of IT capital for other inputs is salient in the industries with less IT capital. Among the sources of IT capital deepening, IT substitution accounts for about 60% of growth in IT capital per hour worked.

JEL Classification: D24, O47

1. Introduction

For the last couple of decades, the U.S. economy has invested in information technology (IT) equipment and software at an extraordinary rate relative to other types of inputs. This rapid accumulation of IT capital per hour worked, known as IT capital deepening, has become one of the major contributors to labor productivity growth in the U.S. economy at both the aggregate and industry levels.[1]

Jorgenson (2001) points out that an essential source of IT capital deepening is the substitution of IT capital for other inputs, induced by a rapid decline in IT prices. As a factor of production, however, the demand for IT capital depends not only on its own price but also on the degree of substitutability between IT capital and other inputs. Thus, it is crucial to investigate the degree of substitutability between IT capital and other inputs in order to explain a rapid IT capital deepening.[2]

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* Department of Economics, Queens College, City University of New York, 65-30 Kissena Boulevard, Flushing, NY 11367 USA; E-mail hchun@qc1.qc.edu.

† IT Industry Division, Korea Information Strategy Development Institute, 1-1 Juam-dong, Kwachun, Kyunggi-do, 427-710, Korea; E-mail mun@kisdi.re.kr; corresponding author.

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[1] Relating IT investment to economic performance, Jorgenson and Stiroh (2000), Oliner and Sichel (2000), and Jorgenson (2001) focus on the IT capital deepening effect on productivity growth associated with the cost-effectiveness of cheaper computers; and Lichtenberg (1995), Brynjolfsson and Hitt (1996, 2003), and Stiroh (2002) concentrate on the productivity growth associated with the technological factors of computers.

[2] There is a large body of literature on the effect of increases in IT capital on the demand for a particular input, such as skilled workers (Berndt, Morrison, and Rosenblum 1992; Berman, Bound, and Griliches 1994; Autor, Katz, and Krueger 1998; Chun 2003). In particular, Morrison (1997) explored the substitution patterns by examining whether the expansion of high-tech capital increases or decreases the demand for other inputs. However, few studies have actually measured the elasticity of substitution between IT capital and various types of other inputs.

In this article, we estimate the elasticities of substitution between IT capital and other factors of production using data on 41 U.S. industries for the period from 1984 to 1999. In a cost function framework, we measure the cross-price elasticity (CPE), the Allen elasticity of substitution (AES), and the Morishima elasticity of substitution (MES). Based on these elasticity estimates, we also explore the quantitative importance of IT substitution in IT capital deepening.

We find that the substitutability of IT capital for other inputs was an essential component in explaining the shift in production technique toward IT capital for U.S. industries. Estimated elasticities of substitution indicate that IT capital is a substitute for other factors of production such as labor, non–IT equipment, structures, and intermediate inputs. In particular, the degree of substitutability between IT capital and other inputs is higher in the manufacturing sector than in the service sector and is higher in the less IT-intensive sector than in the IT-intensive sector.

We also find that IT substitution is an important contributor to IT capital deepening (relative growth of IT capital to hours worked). We decompose IT capital deepening into a substitution effect, an output expansion effect, and a technical change effect. The results show that the substitution of IT capital for other inputs explains about 60% of total IT capital deepening in the U.S. economy for the period from 1985 to 1999.

This article is organized as follows. Section 2 compares various measures of the elasticity of substitution in a cost function model and presents the method for the decomposition of IT capital deepening. Section 3 describes the data used in this study and presents the empirical framework. Section 4 reports estimation results on the elasticities of substitution between IT capital and other inputs and the results on the decomposition of IT capital deepening. Section 5 concludes the article.

2. Elasticity of Substitution and IT Capital Deepening

Elasticity of Substitution

In the case of only two inputs, the elasticity of substitution (σ) between the two inputs x_1 and x_2 is defined as

$$\sigma = \frac{d\ln(x_2/x_1)}{d\ln(p_1/p_2)}, \tag{1}$$

where p_i is the price of input i. Thus, the elasticity of substitution, originally introduced by Hicks (1932), shows the degree of input substitutability by measuring the elasticity of the input ratio with respect to the input price ratio (the marginal rate of technical substitution).[3]

When there are more than two inputs used in production, there is no unique measure of substitutability. A conventional measure is the AES introduced by Allen (1938). As shown in Uzawa (1962), the AES between inputs i and j for a twice-differentiable cost function (C) is defined as

$$\sigma_{ij}^{A} = \frac{C \cdot C_{ij}}{C_i \cdot C_j}, \tag{2}$$

where the subscripts denote partial derivatives with respect to input prices. Inputs i and j are Allen substitutes if $\sigma_{ij}^{A} > 0$ and Allen complements if the inequality is reversed.

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[3] The elasticity of substitution (σ) is also a measure of the curvature of the isoquant.

Using Shephard's lemma, the AES can be written as

$$\sigma_{ij}^{A} = \frac{\varepsilon_{ij}}{S_j}, \tag{3}$$

where ε_{ij} is the CPE of demand for input i with respect to the price of input j, and S_j is the cost share of input j. Equation 3 implies that the AES provides information on input substitutability by measuring changes in the input demand with respect to a change in the price of another input.[4]

Another common measure of input substitutability is the MES, which can be defined in terms of a cost function as

$$\sigma_{ij}^{M} = \frac{p_j C_{ij}}{C_i} - \frac{p_j C_{jj}}{C_j}. \tag{4}$$

We can rewrite the MES in Equation 4 in terms of the cross- and own-price elasticities as

$$\sigma_{ij}^{M} = \varepsilon_{ij} - \varepsilon_{jj}, \tag{5}$$

where ε_{jj} is the own-price elasticity of input j. Equation 5 indicates that the MES measures the percentage change in the ratio of input i to input j, given a 1% change in the price of input j, while the AES measures the percentage change in the input demand (Blackorby and Russell 1989).[5]

In contrast to the AES, the MES is not symmetric, because changes in the input ratio induced by the price of input j can be different from those induced by the price of input i. It is also interesting to note that Allen complements ($\sigma_{ij}^{A} < 0$) can be Morishima substitutes ($\sigma_{ij}^{M} > 0$) if $\varepsilon_{ij} < 0$ and $|\varepsilon_{ij}| < |\varepsilon_{jj}|$. On the other hand, Allen substitutes are always Morishima substitutes.

Since the AES measures absolute input changes, while the MES measures relative input changes, it is possible that the AES and the MES indicate different substitution patterns for two inputs. If input i and j are Allen complements, the definition of the AES implies that a rise in the price of input j makes a firm decrease in the demand for input i. However, whether the rise in the price of input j results in less intensive use of input i relative to input j also depends on the magnitude of own-price elasticity of input j. If the firm's demand for input j is highly responsive to a rise in its own price, the ratio of input i to j can rise. Hence, Allen complementarity does not necessarily imply a fall in the ratio of input i to j with respect to a rise in the price of input j.[6]

Both the AES and the MES can be useful measures of input substitutability depending on the purpose of analysis. Because we are interested in assessing the contribution of IT substitution to IT capital deepening, we need to measure not only the substitutability between IT capital and other inputs but also the effect of input substitution on the ratio of IT capital to other inputs. It will be shown that the MES is particularly useful for assessing the role of input substitution in IT capital deepening given substitutability of IT capital and other inputs.

Decomposition of IT Capital Deepening

In response to changes in input prices, the degree of substitutability between IT capital and other inputs constitutes an essential determinant of IT capital deepening. We decompose the sources

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[4] This indicates that the substitution patterns between inputs implied by the AES are not qualitatively different from those implied by the CPE.

[5] The CPE, the AES, and the MES are evaluated with the assumption that output is held constant.

[6] We thank an anonymous referee for suggesting to us that we clarify differences between the AES and the MES.

of IT capital deepening into an input substitution effect, an output expansion effect, and a technical change effect.

Applying Shephard's lemma to a cost function, we can derive the cost-minimizing input demand that is a function of input prices, output, and the stage of technology. Totally differentiating the derived input demand functions, $x_i(p, y, t)$ and $x_j(p, y, t)$, with respect to time, we may express the relative growth of input i to input j as

$$\frac{\dot{x}_i}{x_i} - \frac{\dot{x}_j}{x_j} = \sum_k (\varepsilon_{ik} - \varepsilon_{jk}) \frac{\dot{p}_k}{p_k} + (\varepsilon_{iy} - \varepsilon_{jy}) \frac{\dot{y}}{y} + \varepsilon_{it} - \varepsilon_{jt}, \tag{6}$$

where a dot over a variable denotes a derivative with respect to time, ε_{ik} is the elasticity of input i with respect to the price of input k, ε_{iy} is the elasticity with respect to output, and ε_{it} is the elasticity with respect to time trend. Equation 6 implies that an increase in the demand of input i relative to input j depends on the relative responsiveness to change in input prices, output expansion, and input-biased technical change.

Since a derived input demand function is homogeneous of degree zero in input prices, we have $\sum_k \varepsilon_{ik} = \sum_k \varepsilon_{jk} = 0$. Substituting the homogeneity condition into Equation 6 and rearranging it, we have

$$\begin{aligned} \frac{\dot{x}_i}{x_i} - \frac{\dot{x}_j}{x_j} = & \underbrace{\underbrace{-\sigma_{ji}^M \left(\frac{\dot{p}_i}{p_i} - \frac{\dot{p}_n}{p_n} \right) + \sigma_{ij}^M \left(\frac{\dot{p}_j}{p_j} - \frac{\dot{p}_n}{p_n} \right)}_{\text{Direct Substitution Effect}} + \underbrace{\sum_{k \neq i, j} (\sigma_{ik}^M - \sigma_{jk}^M) \left(\frac{\dot{p}_k}{p_k} - \frac{\dot{p}_n}{p_n} \right)}_{\text{Indirect Substitution Effect}}}_{\text{Total Substitution Effect}} \\ & + \underbrace{(\varepsilon_{iy} - \varepsilon_{jy}) \frac{\dot{y}}{y}}_{\text{Output Expansion Effect}} + \underbrace{\varepsilon_{it} - \varepsilon_{jt}}_{\text{Input-Biased Technical Change}}, \end{aligned} \tag{7}$$

where p_n is a normalizing input price. Any input price other than the prices of inputs i and j may serve as the normalizing price.

The first three terms on the right side of Equation 7 reflect the effects of input substitution on relative input growth. As input prices change over time, firms need to adjust their inputs, given the substitution possibilities measured by the MES. The substitution effects consist of two components: a direct effect and an indirect effect. The direct substitution effect captures the changes in the growth of input i relative to input j induced by changes in the prices of inputs i and j themselves. On the other hand, the indirect substitution effect indicates the substitution toward inputs i and j induced by changes in the prices of other inputs.

The fourth term is the output expansion effect. Firms need to employ more inputs to produce more output. Unless the production function is homothetic, output expansion can have various effects on the demand for inputs.[7] The last component is the effect of input-biased technical change. If technical change is neutral to all inputs, relative input growth will not be affected.

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[7] In the case of a Cobb-Douglas function with Hicksian neutral technical change, it can be easily shown that relative input growth is completely determined by changes in relative input prices, not only because the MES is one, but also because the function is homothetic with respect to output.

3. Data and Empirical Specification

Data

This study is carried out using data for 41 U.S. private industries from 1984 to 1999. The sample consists of 20 manufacturing and 21 nonmanufacturing industries.[8] We use two data sets published by the Bureau of Economic Analysis (BEA). The *Gross Product Originating* (GPO) provides data on gross output, labor input, and intermediate inputs.[9] Full-time equivalent employees are used as the quantity of labor input. The wage index is constructed by dividing the compensation of employees by the number of full-time equivalent employees.

From the *Fixed Reproducible Tangible Wealth*, we obtained investment data for 61 different types of assets at the industry level.[10] Utilizing these detailed investment data, we construct real capital stocks in 1996 dollars using the perpetual inventory method with geometric depreciation rates.

To measure the cost of capital services, we construct both industry- and asset-specific rental prices as

$$p^f_{k,t} = \frac{1 - itc_{k,t} - u_t z_{k,t}}{1 - u_t}(r^f_t + \delta_k - \pi_{k,t})q_{k,t},$$

where $p^f_{k,t}$ is the rental price of asset k for industry f at time period t, itc is the investment tax credit, u is the corporate income tax rate, z is the present value of capital consumption allowances, r is the nominal internal rate of return, δ is the depreciation rate, π is the asset-specific capital gain, and q is the investment deflator.[11] All tax-related variables are obtained from the Bureau of Labor Statistics (2002).

We will use a long-run cost function to estimate the elasticities of substitution among all inputs. Our use of the internal rate of return takes account of capital utilization and other wedges between the capital stock and services, so it is preferable if a long-run cost function is used.[12] The nominal internal rate of return, r^f_t, is estimated by

$$r^f_t = \frac{CI^f_t - \sum_k tax_{k,t}(\delta_k - \pi_{k,t})p_{k,t}K^f_{k,t}}{\sum_k tax_{k,t}p_{k,t}K^f_{k,t}},$$

where CI^f_t is property-type income obtained from the GPO, $tax_{k,t}$ is $(1 - itc_{k,t} - u_t z_{k,t})/(1 - u_t)$, and $K^f_{k,t}$ is industry f's capital stock of asset type k.

Using the Törnqvist index, the 61 individual capital services for each industry are aggregated into three types of capital services: IT capital, non–IT equipment, and structures. IT capital consists of seven types of computer hardware (mainframe computers, personal computers, direct access storage devices, computer printers, computer terminals, computer tape drives, and computer storage devices),

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[8] We exclude the real estate industry because of the difficulty in measuring capital services.

[9] Many findings indicate that it is not appropriate to use the value-added framework for production analysis at the industry level. See Berndt and Wood (1975), Denny and Fuss (1977), Norsworthy and Malmquist (1983), and Yuhn (1991) for the details of the test of input separability.

[10] See Herman (2000) for a detailed description of the data set.

[11] See Hall and Jorgenson (1967) for the rental price formula and Jorgenson (2001) for a discussion of the importance of capital input prices in the study of information technology.

[12] We are grateful to an anonymous referee for suggesting to us that we should point out the significance of the internal rate of return in the long-run cost function.

three types of software (prepackaged software, custom software, and own-account software), and communications equipment.[13] This definition of IT capital has been used in many recent studies, such as those of Oliner and Sichel (2000), Jorgenson (2001), and Stiroh (2002). However, Berndt, Morrison, and Rosenblum (1992) and Morrison (1997) used a broader measure of IT capital (so-called high-tech capital) that includes other information-related equipment, such as office equipment, instruments, and photocopy and related equipment, in addition to the IT capital defined in our study.

Nonresidential equipment services, except those included in IT capital services, are aggregated into non–IT equipment services. All types of nonresidential structures define structures services.

Table 1 shows the composition of the three types of capital services (IT, non–IT equipment, and structures) for 41 U.S. industries in 1984 and 1999.[14] The IT composition in the first column is defined as the ratio of IT capital services to the sum of the three capital services. The table also presents interesting variations in the composition of IT capital services across industries and over time periods.

IT shares in these years were high for instruments and related products, industrial machinery and equipment, and electronic and other electric equipment within the manufacturing sector, as well as for communications, wholesale trade, and business services within the service sector. In general, IT was more intensively used in the service sector than in the manufacturing sector. Within the manufacturing sector, IT shares were higher in the durable goods sector than in the non–durable goods sector.

Table 1 also indicates that the IT shares for all industries have dramatically increased from 1984 to 1999. Rapid increases in the IT shares were not confined to IT-intensive industries. The IT shares in less IT-intensive industries, such as construction and agriculture, forestry, and fishing, also grew very rapidly. The composition of IT capital services rose, on average, from 3.5% to 28.6%, but the compositions of non–IT equipment and structures fell from 49.8% to 39.0% and from 46.7% to 32.4%, respectively.

Table 1 indicates that there has been a substitution toward IT capital and away from both non–IT equipment and structures. Fuller quantification of the degree of substitutability between IT capital and other inputs would provide useful insights into both changes in the production structure and the role of IT substitution in the accumulation of IT capital in U.S. industries.

Empirical Specification

In order to estimate the elasticities of substitution between IT capital and other inputs, without imposing *a priori* restrictions on the elasticities, we employ the symmetric generalized McFadden (SGM) cost function.[15] The long-run SGM cost function with the five inputs of labor

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[13] A recent comprehensive revision of the *National Income and Product Accounts* published by the BEA includes expenditures on software as a fixed investment.

[14] The IT share measured by capital services is higher than that measured by the capital stock, because the cost of IT capital services includes the high rate of depreciation and the rapid decline in the investment prices. See Jorgenson (2001) for a comparison of the IT capital stock and services in the aggregate U.S. economy over the period ranging from 1948 to 2000.

[15] The SGM function is a flexible functional form proposed by Diewert and Wales (1987). Generally speaking, a flexible functional form is a functional form that has enough parameters to provide a second-order approximation to an arbitrary twice continuously differentiable function. In contrast to the nonflexible functional forms, such as the Cobb-Douglas or the CES functions, flexible functional forms do not impose *a priori* constraints on the elasticity of substitution between inputs.

Table 1. Composition of Capital Services for 41 U.S. Industries[a]

	1984			1999		
Industry	IT	Non–IT Equipment	Structures	IT	Non–IT Equipment	Structures
Agriculture, mining, and construction sector						
Agriculture, forestry, and fishing	0.001	0.563	0.437	0.024	0.588	0.389
Mining	0.007	0.335	0.659	0.062	0.288	0.650
Construction	0.001	0.653	0.347	0.094	0.641	0.265
Manufacturing sector						
Lumber and wood products	0.004	0.598	0.398	0.075	0.556	0.369
Furniture and fixtures	0.010	0.440	0.550	0.164	0.425	0.411
Stone, clay, and glass products	0.011	0.630	0.359	0.136	0.605	0.259
Primary metal industries	0.007	0.657	0.336	0.091	0.620	0.290
Fabricated metal products	0.007	0.604	0.389	0.142	0.545	0.313
Industrial machinery and equipment	0.050	0.591	0.359	0.446	0.355	0.199
Electronic and other electric equipment	0.046	0.586	0.368	0.275	0.466	0.259
Transportation equipment	0.019	0.716	0.265	0.212	0.589	0.199
Instruments and related products	0.047	0.539	0.413	0.499	0.291	0.211
Miscellaneous manufacturing industries	0.008	0.453	0.539	0.144	0.459	0.397
Food and kindred products	0.006	0.538	0.456	0.093	0.542	0.365
Tobacco products	0.010	0.467	0.523	0.104	0.419	0.477
Textile mill products	0.008	0.681	0.311	0.206	0.573	0.221
Apparel and other textile products	0.013	0.463	0.524	0.163	0.402	0.435
Paper and allied products	0.005	0.786	0.209	0.094	0.745	0.161
Printing and publishing	0.020	0.612	0.368	0.436	0.337	0.227
Chemicals and allied products	0.006	0.631	0.363	0.129	0.586	0.284
Petroleum and coal products	0.003	0.388	0.610	0.025	0.484	0.491
Rubber and miscellaneous plastics products	0.008	0.728	0.264	0.167	0.661	0.172
Leather and leather products	0.006	0.421	0.573	0.121	0.372	0.507
Service sector						
Transportation	0.024	0.711	0.264	0.210	0.567	0.223
Communications	0.475	0.110	0.416	0.590	0.146	0.264
Electric, gas, and sanitary services	0.013	0.394	0.592	0.106	0.357	0.537
Wholesale trade	0.067	0.538	0.395	0.546	0.256	0.199
Retail trade	0.018	0.359	0.623	0.175	0.301	0.524
Bank and security	0.046	0.487	0.467	0.425	0.350	0.225
Insurance	0.066	0.410	0.523	0.419	0.292	0.289
Hotels and other lodging places	0.009	0.196	0.795	0.072	0.214	0.714
Personal services	0.006	0.381	0.614	0.108	0.353	0.539
Business services	0.096	0.616	0.288	0.519	0.338	0.144
Auto repair, services, and parking	0.008	0.945	0.047	0.042	0.934	0.024
Miscellaneous repair services	0.012	0.638	0.350	0.270	0.467	0.263
Motion pictures	0.030	0.619	0.351	0.474	0.357	0.169
Amusement and recreation services	0.035	0.392	0.573	0.073	0.348	0.579
Health services	0.013	0.339	0.648	0.131	0.320	0.549
Legal services	0.048	0.308	0.643	0.347	0.215	0.438
Educational services	0.022	0.265	0.713	0.238	0.104	0.658
Other services	0.041	0.282	0.677	0.386	0.201	0.413
Average	0.035	0.498	0.467	0.286	0.390	0.324

[a] Capital compositions in all columns are calculated as the ratio of each capital service to the sum of the three capital services.

(*L*), non–IT equipment (*E*), structures (*S*), IT equipment and software (*O*), and intermediate inputs (*M*), is defined as

$$
\begin{aligned}
C(p,y,t) = {} & \frac{1}{2}\sum_i\sum_j a_{ij}p_ip_jy\left(\frac{1}{\sum_i \theta_i p_i}\right) + \sum_i a_{iy}p_iy + \sum_i a_ip_i \\
& + \sum_i a_{it}p_ity + a_t\left(\sum_i \alpha_i p_i\right)t + a_{yy}\left(\sum_i \beta_i p_i\right)y^2 \\
& + a_{tt}\left(\sum_i \gamma_i p_i\right)t^2y, \\
& i,j = L,E,S,O,M \quad \text{and} \quad a_{ij} = a_{ji},
\end{aligned}
\tag{8}
$$

where p_i denotes the price of input i, y denotes gross output, and t denotes the state of technology.[16]

Utilizing $\sum_i \alpha_i p_i$, $\sum_i \beta_i p_i$, and $\sum_i \gamma_i p_i$, the SGM cost function accounts for technical change and returns to scale, while preserving its flexibility and homogeneity. Diewert and Wales (1987) also introduced $\sum_i \theta_i p_i$, so that the input demand equations are symmetric. The parameters θ_i, α_i, β_i, and γ_i are preselected by the researcher rather than estimated. In order to identify all of the parameters in the cost function, we need to impose symmetry restrictions, thus:

$$\sum_j a_{ij} = 0. \tag{9}$$

Applying Shephard's lemma to the SGM cost function, input demand equations are derived. To reduce possible heteroskedasticity, the input demand equations are converted into input intensity equations as

$$
\begin{aligned}
\frac{x_i}{y} = {} & \left[\sum_i a_{ij}p_j\right]\left(\frac{1}{\sum_i \theta_i p_i}\right) - \theta_i\left[\frac{1}{2}\sum_i\sum_j a_{ij}p_ip_j\right]\left(\frac{1}{\sum_i \theta_i p_i}\right)^2 \\
& + a_{iy} + a_iy^{-1} + a_{it}t + a_t\alpha_ity^{-1} + a_{yy}\beta_iy + a_{tt}\gamma_it^2,
\end{aligned}
\tag{10}
$$

where x_i is the quantity of input i. Since the long-run cost function in Equation 8 contains no additional information, the input intensity equations define system of equations to be estimated.

4. Estimation Results

The system of input intensity equations described in Equation 10 provides a seemingly unrelated regressions (SUR) model, because it is likely that the disturbances in the input intensity equations are correlated with each other.[17] In general, the SUR model gives more efficient estimates than the separate regressions of a single equation because the SUR model utilizes more information. Therefore, we jointly estimated the five input intensity equations using the maximum likelihood estimator.[18]

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[16] Physical capital is often considered to be a quasi-fixed input in a dynamic cost function model, such as those of Morrison (1997) and Nadiri and Prucha (2001), and this may be a more realistic assumption. However, this study uses a static long-run cost function, which enables us to measure not only the elasticity of substitution induced by factor prices but also the elasticity of substitution between different types of capital services.

[17] This implies that the off-diagonal elements of the residual covariance matrix may be non-zero.

[18] Our cost function model assumes that input prices and output are exogenous. To correct for possible endogeneity, we also estimated the model using the 3SLS with lagged variables as instruments. The estimation results were not qualitatively different.

Following Diewert and Wales (1987), the preselected parameters (θ_i, α_i, β_i, and γ_i) were set to be the average cost shares of inputs for all industries so that the estimated elasticities are invariant to scale changes in the units of measurement. The industry dummy variables for intercepts were included in all the input intensity equations. We found first-order autocorrelation in the residuals of the system of equations and corrected for it in the estimation procedure.[19]

Because the concavity of the cost function with respect to input prices was not satisfied with the initial estimation, we imposed concavity restrictions using the method proposed by Diewert and Wales (1987). We performed the log-likelihood test and could not reject concavity restrictions (LR[10] = 2.6, with a critical value of $\chi^2_{0.05} = 18.31$). Parameter estimates are presented in Table 2.

Elasticities of Substitution between IT Capital and Other Inputs

To measure substitution possibilities between inputs, we calculated the CPE, the AES, and the MES using the parameter estimates in Table 2. Table 3 presents three types of elasticities for each sector. Sectoral elasticities are aggregated from the industry-level elasticities using weights equal to shares of the industry output.[20] The standard error for elasticity is evaluated at each mean value using the delta method.[21]

The top panel in Table 3 reports the estimated CPE associated with IT capital. Except for intermediate inputs, the CPE estimates show that IT capital is a substitute for labor, non–IT equipment, and structures. With regard to IT capital and intermediate inputs, the signs of both ε_{MO} and ε_{OM} are negative, which indicates that IT capital is a complement for intermediate inputs. The complementarity of IT capital and intermediate inputs implies that rapid falls in IT prices could induce increases in the demand for intermediate inputs in the production process.

The second panel in Table 3 presents the AES between IT capital and other inputs. As shown in Equation 3, the AES estimates indicate the same substitution patterns as the CPE. While IT capital is an Allen substitute for labor, non–IT equipment, and structures, it is an Allen complement for intermediate inputs.

Thompson and Taylor (1995) pointed out that relatively small changes in the cost share of an input could create substantial differences in the AES estimates when the cost share of the input is small. The second panel shows that the AES estimates of labor and IT are about five times greater in the manufacturing sector than in the service sector because of the difference in their IT shares, although the CPE estimates are close to each other.

Unlike the CPE and the AES, the MES measures a change in the ratio of inputs to a change in input prices. These estimates are reported in the third panel of Table 3 and indicate that IT capital is a Morishima substitute for labor, non–IT equipment, and structures.

The MES estimates are asymmetric, which is completely natural, because changes in the ratio of IT capital to other input depend on which input price changes. The weighted averages of the MES between labor and IT capital for 41 industries, σ^M_{LO} and σ^M_{OL}, are 0.509 and 0.720, respectively. The

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[19] We assume that a vector of disturbances, U_t, in the system of equations follows a first-order vector autoregressive process, $U_t = RU_{t-1} + \omega_t$, where R is an autocovariance matrix and ω_t is a vector of independently and identically normally distributed random error terms. Assuming that R is diagonal and that all diagonal elements of R equal ρ, we estimate ρ along with the other parameters in the system of equations. See Berndt and Savin (1975) and Berndt (1991) for more details on the vector autocorrelation in the system of equations.

[20] A full set of the three elasticities for these 41 industries is available upon request.

[21] Given a vector of parameter estimates β, a function of the estimated parameters, $f(\beta)$, is asymptotically normally distributed with the variance-covariance matrix $G'VG$, where G is the first derivative of f with respect to β and V is the variance-covariance matrix of β.

Table 2. Parameter Estimation Results: 41 U.S. Industries, 1984–1999[a]

Parameter	Estimate	Standard Error
a_L	5.0446	0.7465
a_E	1.5991	0.2181
a_S	1.8923	0.2222
a_O	0.3164	0.1206
a_M	−.2046	1.4493
a_{LY}	0.1450	0.0279
a_{EY}	0.0323	0.0072
a_{SY}	0.0437	0.0077
a_{OY}	−0.0099	0.0027
a_{MY}	0.2066	0.0492
a_{LT}	-0.0666	0.0159
a_{ET}	−0.0143	0.0040
a_{ST}	−0.0189	0.0044
a_{OT}	0.0005	0.0013
a_{MT}	−0.0998	0.0277
a_{LL}	−0.0519	0.0072
a_{EE}	−0.0071	0.0022
a_{SS}	−0.0020	0.0007
a_{OO}	−0.0023	0.0005
a_{LE}	0.0041	0.0172
a_{LS}	0.0003	0.0091
a_{LO}	0.0043	0.0014
a_{ES}	0.0006	0.0010
a_{EO}	0.0018	0.0006
a_{SO}	0.0014	0.0004
a_T	−0.2148	0.0688
a_{TT}	0.0025	0.0006
a_{YY}	−0.0009	0.0001
ρ	0.9234	0.0058
Input Intensity Equation	Standard Error	R^2
Labor	8.96E−03	0.9951
Non–IT Equipment	3.59E−03	0.9940
Structures	1.14E−05	0.9967
IT Capital	2.84E−03	0.9928
Intermediate Inputs	5.18E−04	0.9752
Log of Likelihood		12303.1

[a] Parameter estimates for the industry dummy variables are not reported.

findings imply that the ratio of labor to IT capital is more responsive to labor price changes than to IT price changes. In other words, an increase in the price of labor induces more substitution of IT capital for labor input than does a decrease in the price of IT.

However, the ratios of non–IT equipment and structures to IT capital are more responsive to changes in the price of IT than to changes in the prices of the two non-IT capital services. Thus, economic policies designed to stimulate substitution toward IT capital and away from other forms of capital by altering IT prices may be more effective than those designed to stimulate IT investment by altering the prices of other types of capital. Furthermore, evidence on the substitution of IT for non-IT capital implies a shift in the composition of aggregate capital toward shorter-lived assets, which results in an increase in the service flows from the given total capital stock.

Table 3. Elasticities of Substitution between IT and Other Inputs, 1984–1999[a] (Mean Values)

	Manufacturing Versus Service				IT-Intensive Versus Less-IT-Intensive		
	Durable	Nondurable	Total Manufacturing	Service	IT-Intensive	Less-IT-Intensive	Total
Own-Price and Cross-Price Elasticities							
ε_{LO}	0.028***	0.054***	0.040***	0.020***	0.018***	0.032***	0.027***
ε_{EO}	0.060***	0.054***	0.057***	0.076***	0.059***	0.066***	0.065***
ε_{SO}	0.087***	0.071***	0.079***	0.046***	0.043***	0.060***	0.056***
ε_{MO}	−0.010**	−0.010**	−0.010**	−0.020***	−0.017**	−0.016**	−0.017**
ε_{OL}	0.608***	0.954***	0.767***	0.345***	0.125***	0.811***	0.548***
ε_{OE}	0.239***	0.379***	0.304***	0.132***	0.050***	0.321***	0.217***
ε_{OS}	0.187***	0.292***	0.236***	0.114***	0.041***	0.260***	0.176***
ε_{OM}	−0.472**	−0.723**	−0.588**	−0.298***	−0.105**	−0.680**	−0.459**
ε_{LL}	−0.166***	−0.331***	−0.242***	−0.130***	−0.116***	−0.201***	−0.172***
ε_{EE}	−0.116***	−0.103***	−0.110***	−0.158***	−0.125***	−0.131***	−0.133***
ε_{SS}	−0.068***	−0.053***	−0.061***	−0.045***	−0.037***	−0.053***	−0.049***
ε_{MM}	−0.050	−0.048	−0.049	−0.095**	−0.082**	−0.073**	−0.078**
ε_{OO}	−0.562***	−0.902***	−0.719***	−0.293***	−0.111***	−0.712***	−0.481***
Allen Elasticities of Substitution							
σ^{A}_{LO}	2.322***	7.737***	4.817***	0.775***	0.307***	3.754***	2.416***
σ^{A}_{EO}	4.462***	6.201***	5.264***	4.563***	1.236***	6.837***	4.695***
σ^{A}_{SO}	6.765***	7.584***	7.142***	2.376***	0.817***	6.042***	4.069***
σ^{A}_{MO}	−0.755**	−1.023**	−0.878**	−0.801***	−0.259**	−1.380**	−0.948**
Morishima Elasticities of Substitution							
σ^{M}_{LO}	0.590***	0.956***	0.759***	0.313***	0.129***	0.744***	0.509***
σ^{M}_{EO}	0.622***	0.956***	0.776***	0.369***	0.170***	0.777***	0.547***
σ^{M}_{SO}	0.649***	0.973***	0.798***	0.340***	0.154***	0.771***	0.537***
σ^{M}_{MO}	0.552***	0.892***	0.709***	0.273***	0.094***	0.696***	0.465***
σ^{M}_{OL}	0.773***	1.284***	1.009***	0.474***	0.241***	1.013***	0.720***
σ^{M}_{OE}	0.355***	0.482***	0.414***	0.290***	0.175***	0.452***	0.350***
σ^{M}_{OS}	0.256***	0.345***	0.297***	0.160***	0.078***	0.313***	0.225***
σ^{M}_{OM}	−0.421*	−0.675*	−0.538*	−0.204*	−0.023	−0.608**	−0.382**

[a] The elasticities are the mean values over the period from 1984 to 1999. The service sector excludes not only the manufacturing sector but also agriculture, forestry, and fishing, mining, and construction industries. The IT-intensive sector includes 13 industries: industrial machinery and equipment, electronic and other electric equipment, instruments and related products, printing and publishing, communications, wholesale trade, bank and security, insurance, business services, miscellaneous repair services, motion pictures, legal services, and other services.

* Significant at the 10% level.

** Significant at the 5% level.

*** Significant at the 1% level.

Considering the substitution possibilities between IT capital and intermediate inputs, we find that they are Morishima substitutes when the price of IT changes, while they are Morishima complements when the price of intermediate inputs changes. As shown in Equation 5, Allen complements can be Morishima substitutes, because the MES measures a change in the input ratio. Falls in IT prices increase the demand for intermediate inputs because IT and intermediate inputs are Allen complements. However, the own-elasticity of IT capital is sizable enough to offset the decrease of intermediate inputs demand. This implies that as IT prices fall, firms use IT capital more intensively with respect to intermediate inputs, in spite of Allen complementarity between IT capital and intermediate inputs.

Intermediate inputs consist of energy, purchased services, and materials supplied by other industries.[22] Therefore, the substitutability of IT capital and intermediate inputs characterizes not only the production structure but also the inter-industry transactions. A few recent studies have found that the adoption of IT affects the structure of demand for intermediate inputs. Brynjolfsson and Hitt (2000) suggested that the adoption of IT could result in a change in the supply chain of the firm. The adoption of IT enables firms to manage their suppliers in an effective and efficient way, which may make it possible for firms to transfer their production processes to their suppliers. In a similar vein, Wolff (2002) also found that IT affects the composition of intermediate inputs at the industry level.

Comparing the MES estimates across sectors, we find that the manufacturing sector has greater elasticities of substitution between IT capital and other inputs than does the service sector. Within the manufacturing sector, the degrees of substitutability associated with IT capital are higher in the non–durable goods sector than in the durable goods sector. These differences in the elasticities of substitution become salient when we group industries into the IT-intensive sector and the less-IT-intensive sector.[23] The MES estimates of IT and other inputs for the less-IT-intensive sector are approximately five times larger that those for the IT-intensive sector.

Overall, estimates of elasticities of substitution indicate that IT capital is a substitute for other inputs. Our results indicate that a rapid increase in IT investment can be attributed to the substitution of IT capital for other inputs in response to declines in IT prices. In particular, IT capital is more substitutable for labor and other capitals than for intermediate inputs.

Decomposition of IT Capital Deepening

Table 4 shows IT capital deepening and its decomposition into direct and indirect IT substitution effects, an output expansion effect, and a technical change effect over the period from 1985 to 1999. In the total U.S. private economy, IT capital services per hour worked grew at 18.76% annually. IT capital deepening was higher in the manufacturing sector than in the service sector. In general, those sectors using IT capital less intensively experienced a higher level of IT capital deepening.

The second and third columns of Table 4 show both direct and indirect effects of substitution on IT capital deepening. The direct substitution effect accounts for about 56% of the IT capital deepening in the U.S. private economy, whereas the indirect effect explains about 4%. The strong direct substitution effect provides support for the hypothesis that a swiftly falling IT price is a primary catalyst for IT capital deepening.

Since the MES estimates are different across sectors, the contributions of the direct substitution effect to the growth of IT capital per hours worked vary across sectors. The direct substitution effect explains about two-thirds of IT capital deepening in the manufacturing sector, while it explains one-third of IT capital deepening in the service sector. There are remarkable differences in the direct substitution effects between the IT-intensive and the less-IT-intensive sector. Because of higher substitutabilities between IT capital and other inputs in the less-IT-intensive sector, the substitution

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[22] We also examined the elasticity of substitution in the subsample of 20 manufacturing industries with the three intermediate inputs. The CPE and the AES estimates indicate that IT capital is a substitute for purchased services but a complement for energy and materials. With a change in IT price, the MES estimates show that IT and the three intermediate inputs are substitutes. Detailed estimation results are available upon request.

[23] According to the ratio of IT stock to the total capital stock in 1996, we split the sample into two subsamples, the IT-intensive sector and the less-IT-intensive sector. Since there exists a significant gap in the ratio between the 13th industry (electronic and other electric equipment) and the 14th industry (miscellaneous manufacturing), we define the first 13 industries with higher ratios as the IT-intensive sector.

Table 4. Sources of IT Capital Deepening, 1985–1999[a]

Sector	IT Capital Deepening	Direct Substitution Effect	Indirect Substitution Effect	Output Expansion Effect	Residuals
Manufacturing	22.98	16.71	2.39	−4.06	7.94
Durable	21.60	12.44	1.82	−4.18	11.52
Nondurable	26.14	21.76	3.04	−3.04	4.38
Service	17.41	6.16	0.12	−4.01	15.13
IT Intensive	18.05	2.77	0.12	−0.80	15.95
Less IT Intensive	20.26	16.19	1.23	−5.24	8.08
Average	18.76	10.55	0.76	−4.71	12.16

[a] All values are average annual percentage rates of growth. IT capital deepening is defined as growth rate of IT capital services minus growth rate of hours worked. Residuals are calculated as IT capital deepening minus the sum of the three effects: direct and indirect substitution effects and output expansion effect.

effect is much stronger in the less-IT-intensive sector than in the IT-intensive sector. Our findings on the substitution effects imply that labor productivity growth through IT capital deepening, particularly for industries with less IT capital, will continue as IT prices fall.

The fourth column of Table 4 presents the effect of output expansion on IT capital deepening. The negative output expansion effect indicates that the demand for IT capital increases less than that for labor with output expansion. Residuals in the last column include the effect of input-biased technical change and other exogenous effects on the accumulation of IT capital per hour worked. Residuals also explain a substantial portion of IT capital deepening, which implies that the demand for IT capital can be attributed to changes in the business environment, such as the need for better customer services and for higher quality products.

5. Conclusion

Using data on 41 U.S. industries from 1984 to 1999, we provided estimates of the elasticities of substitution between IT capital and other factors of production. Our estimates of the cross-price, the Allen, and the Morishima elasticities of substitution show that IT capital is a substitute for labor, non–IT equipment, structures, and intermediate inputs.

To quantify the role of IT substitution in IT capital deepening, we decomposed IT capital deepening into an input substitution effect, an output expansion effect, and a technical change effect. We found that about 60% of IT capital deepening is attributable to the substitution of IT capital for other inputs. The findings indicate that the relentless decline in IT prices makes IT investment an important source of labor productivity growth in the U.S. economy.

Our findings on the degrees of IT substitution and their contributions to IT capital deepening have important implications for U.S. economic growth. The rapid decline in IT prices is rooted in the productivity growth of IT-producing industries. Therefore, to predict the role of IT investment in productivity growth in IT-using industries, we have to pay attention not only to the production structure of IT-using industries but also to productivity growth in IT-producing industries.

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