The Price and Quantity of IT-Related Intangible Capital

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Abstract

The new business practices and information structures associated with IT-related intangible capital (ITIC) account for a significant fraction of the market value of modern firms. We use a newly-constructed IT data series along with Hall's Quantity Revelation Theorem to create ITIC price and quantity measures in a panel of US firms. We find that that ITIC values dropped significantly after the dot-com bust, but that this was mostly due to fluctuations in price. ITIC quantities rose steadily until about 2000, and then begin to fall but at a slow rate. As a fraction of firms' total assets, ITIC quantities rose from about 20% in 1995 to about 40% in 2006. We also estimate that ITIC depreciates at a rate of about 7% a year, which is closer to the estimated depreciation rate for physical capital than for R&D capital.

Introduction

As the economy becomes more digital, intangible assets are increasingly important. Yet they remain poorly measured. Basic distinctions, such as price and quantity have remained elusive, making economic and business inferences difficult.

The value of intangible assets has grown dramatically in recent years and much of this growth, especially since the mid 1990's, can be attributed to digitization. In particular, the new work practices, information structures, and employee skill-mix that accompany IT investment comprise a growing category of IT-related intangible capital (hereafter, referred to as ITIC)[1] (Hall 2001; Brynjolfsson, Hitt, and Yang 2002; Bresnahan, Brynjolfsson, and Hitt 2002). ITIC investments are similar to tangible capital investments, such as plants and equipment. Much as units of physical capital enable the conversion of raw materials to goods, units of ITIC enable the conversion of information and ideas into products and services. Firms that accumulate more ITIC will have superior innovative and productive capacity, and the market value of these assets should reflect the net present value of the cash flows that they can generate.

Prior work provides evidence that firms' investments in ITIC are associated with significant market value (Brynjolfsson, Hitt, and Yang 2002; Saunders 2010). The value associated with these intangible assets, however, provides limited guidance about their potential for producing long-term productivity growth because it is the *stock* of IT-related intangible capital, rather than its value, which affects productivity. If ITIC is expensive, high values reflect only small improvements in productive capacity. On the other hand, if ITIC prices are low, high values reflect the development of large amounts of productive capacity in US firms, which has positive implications for long-run growth. Unfortunately, the stock of IT-related intangibles has proven more difficult to measure than its value. The flow of investment into this new type of capital is generally invisible to researchers, so methods similar to those used to generate R&D capital stock measures cannot be easily used here. Alternatively, one might use

[1] In other work, IT-related intangible capital has been referred to as "organizational capital", "e-capital", or "IT-related organizational capital".

market prices (such as a lease or resale price) to derive quantities if values are available. However, there are no markets through which prices for IT-related intangible capital can be observed.

This paper uses a new IT data series, along with methods pioneered by Robert Hall, to address these issues (Hall, 2001). Hall argues that under reasonable conditions, the quantity of a firm's capital can be inferred from the value of its securities. This method can be applied to recover quantities of ITIC. However, the recursive nature of the approach requires a longer IT series than has historically been available in firm-level panels. A contribution of this paper is the use of a longer IT data series that enables using the methods described by Hall to measure ITIC quantities in US firms. To the best of our knowledge, this is the first paper that moves beyond measuring the value of IT-related intangibles to measuring the amount of ITIC in firms, and is therefore important for advancing our understanding of how firms' massive investments into IT-related restructuring might translate into differences in productivity across time, firms, or countries. Specifically, the paper has two goals. *First*, we estimate how the quantity of ITIC has changed over time in US firms. *Second*, we estimate how quickly ITIC depreciates.

The answers to these questions are important because understanding the accumulation, depreciation, and growth characteristics of IT-related intangibles is critical for guiding managerial investment and growth policy. If growth in ITIC value is being driven by price changes rather than quantity, it suggests a high cost of capital acquisition and significant rents to firms endowed with these assets. If instead, changes in value are due to increases in the quantity of capital stock, the trend in IT-enabled growth will extend into the future as stocks of ITIC are accumulated and because of the likelihood of future increases in these stocks. Understanding this relationship also requires understanding how quickly ITIC depreciates, which influences whether the contribution of these assets to growth will persist into the future or whether maintaining levels of ITIC requires ever increasing investments at the expense of reduced output.

This paper makes an important contribution to the IT value literature. It provides evidence on how the value, quantity, and price of ITIC have changed over the last two decades. By measuring changes

in ITIC quantities, we can better understand its effects on productivity. Our estimates suggest that except for a brief slowdown just after 2001, quantities of ITIC have been steadily rising through the end of our panel in 2005. On average, ITIC levels appear to be about one-third that of physical capital and the data suggests that the growth rate of these assets exceeds that of physical capital through the end of our panel. Our estimates imply that ITIC depreciates at a rate of about 6-8% a year, which is close to the rate of physical structures, and much slower than other intangible assets such as R&D or advertising. We conclude the paper with a discussion of the growth implications of these findings and suggestions for future research in this area.

Using a new IT data series

The approach to intangible capital measurement used in this study relies on the availability of new panel data describing firm-level IT investment. For the purposes of this analysis, this new data series offers two advantages: 1) it spans a longer time period than any comparable IT data and 2) it is available after the dot-com crash which allows us to test how much of the value of IT–related intangibles in the late 1990's was attributable to investor mispricing. In the following sections, we summarize the construction and salient properties of these data. A more complete discussion of this data series and an application to productivity measurement is provided in Tambe and Hitt (2011). Our benchmark comparisons provide evidence that concerns related to sampling or measurement error with this new data source are not a serious limitation.

Data

This study uses data based on IT employment for about 36,000 firm-years from 1987 to 2005. To the best of our knowledge, it is one of the more complete firm-level IT panels that has been assembled.[2] This is not the first study to use IT employment as a measure of IT spending (Lichtenberg 1995; Brynjolfsson and Hitt 1996), but the consistency of the time series over more than two decades make the

[2] The US Census Bureau tabulates IT data for plants, which can be aggregated to the firm level. However, the information technology questions on the economic census only appear sporadically and are not consistent from year to year.

methods used in this paper feasible. Notably, these data extend through 2005, allowing us to test how key economic relationships are affected by the 2001 dot-com crash.

These IT labor measures use data on the employment histories of a large fraction of US IT workers to infer the distribution of IT employment in US firms. The data were obtained in 2007 through a partnership with a leading online jobs board on which individuals post employment histories, including information for each job they have held on employer, job title, and years spent at the firm. Employer data include name, size, and industry. Because these workers are jobs board participants, they are more oriented towards external labor markets and somewhat more comfortable with Internet based technologies than the average worker. To uncover any systematic differences of concern, we compare the demographic characteristics of workers in our sample with those of IT workers in the 2006 Current Population Survey (CPS), a monthly survey of about 50,000 households conducted by the Bureau of the Census. Because the CPS is randomly sampled from the civilian population, IT workers who appear in the survey are a random sample drawn from the population of all information technology workers. Table 1 shows some demographic comparisons between the IT workers from the jobs board and the IT workers that appear in the Current Population Survey. The distribution of education of IT workers in our sample is not significantly different from the average age of workers in the CPS sample. However, as expected, job tenure is somewhat shorter.

Table 1. Demographic Comparison with Current Population Survey

	Matched Resume Sample	CPS 2006[1]
Education		
High School Degree or Less	24.7	25.1
Vocational Degree	2.8	0.8
Two Year Degree	14.3	10.8
Four Year Degree	38.8	42.8
Graduate Degree	18.6	18.9
Doctorate	0.7	1.7
Average Job Tenure	4.00	6.33
[1]Source: Current Population Survey (CPS), 2006		

The employment histories of these IT workers are used to construct measures of the distribution of IT employment in public firms over a number of years. Because the employment histories in these data are sampled from the underlying population of IT workers, sampling error in the measures will tend to

bias OLS estimates downward by an amount related to the share of the total variance of the measure attributable to the variance of the sampling error. However, the sample size suggests that any measurement error should be much less than in the CI IT capital data, which may be as high as 30-40% of the total measure variance (Brynjolfsson & Hitt 2003). Later in this analysis, we show that these IT labor measures are reasonably robust to measurement error by using instrumental variables to correct the measurement error in our estimates. If sampling concerns are a serious limitation of these measures, this will manifest in our IV estimates as long as the source of error is uncorrelated with the error term in the CI data, which we use as an instrument.

A second potential source of measurement error is IT outsourcing. Because we only capture labor inputs employed at the firm, the labor resources that a firm dedicates to IT infrastructure will be misrepresented if a significant amount of work is handled through outsourcing relationships. This is only a problem for our estimates if outsourcing is correlated with IT size – for instance, if everyone outsources equally this will not impact our estimates. However, we can test the effects of this type of measurement error on a subsample of our data by directly introducing IT outsourcing measures collected through a 2008 survey in which managers reported what percentage of the IT budget was spent on outsourced services. The average firm in this sample spent about 15.2% of its IT budget on outsourced services, and the correlation between IT outsourcing and 2005 levels of IT employment is not significantly different than zero, which suggests that omitting outsourcing will not bias our IT estimates. However, in our regression analyses, we report robustness tests that control for IT outsourcing levels.

We can relate these IT employment numbers to IT capital stock measures by considering a model where firms invest in four production inputs: IT capital and non-IT capital, and IT-related labor and non-IT labor.

(1) $$Y = \alpha_0 C_0 + \alpha_{IT} C_{IT} + \beta_0 L_0 + \beta_{IT} L_{IT}$$

In equilibrium, IT labor is related to the stock of IT capital through the ratio of their factor shares, the rental price of IT capital (r_{IT}), and the wage rate for IT labor (w_{IT}).

$$r_{IT}C_{IT} = \left(\frac{\alpha_{IT}}{\beta_{IT}}\right) w_{IT}L_{IT} \tag{2}$$

In equilibrium, a firm's total IT employment is related to IT capital stocks by a scale factor. Therefore, our IT employment measures can be used in a production function or market value regression in the same way as computer capital stocks. For the productivity analyses later in this section, variables are in log-levels, so interpretation of elasticity estimates will be unaffected by the scaling factor when comparisons are conducted between firms in the same year. In our market value regressions, our ITIC value measures, which form the core of our analysis, will not be affected by these changes.

Benchmarking the IT Measures

These IT measures are an alternative to capital expenditures for measuring IT capital stocks. These measures are less vulnerable to measurement error than expenditure based measures, so measurement error induced bias should not be an especially significant problem with our estimates. Furthermore, there is evidence to suggest, that in recent years a greater share of IS spending has been devoted to labor costs than to capital (Brynjolfsson, Fitoussi, and Hitt 2006). Despite these differences, however, capital expenditures and IT employment should be correlated with one another – firms that invest heavily in IT equipment require staff to manage and maintain infrastructure (conditional on IT labor outsourcing, which is discussed separately below). To assess the accuracy of these data for measuring IT investment, we compare our measures with several other widely used firm-level measures of IT spending, including computer capital expenditures. These computer expenditure measures are derived from the Computer Intelligence Infocorp (CI) described above, a database which has been used in a number of studies related to information technology investment patterns (e.g., Brynjolfsson and Hitt 2003; Forman 2005; Tallon and Kraemer 2006). To create this database, data from 25,000 sites are aggregated to form measures for Fortune 1,000 companies that represent the total population in a given year. The database is compiled from telephone surveys used to gather detailed information about the ownership of computer equipment and related products. Most sites are updated at least annually, with more frequent sampling for larger sites. The year-end state of the database for each year is used for

computer measures. From these data we obtained the total capital stock of computers (central processors, personal computers, and peripherals).

Table 2 shows correlations between the IT labor measures and external sources of IT data, including the CI data. The ComputerWorld, InformationWeek, and MIT surveys reflect IT labor, measured either in IT labor expense or total IT employees. The correlations with all of these data sources are high enough to indicate that the IT labor panel used in this study is a fairly good representation of IT spending across a number of different time periods.

Table 2. Correlations Among Different Measures of IT Spending

	ComputerWorld[a]	InformationWeek[c]	CI[b]	MIT[c]	MIT[d]
Years	1988-1992	1994-1995	1987-2000	2001	2006*
Correlation	.63	.46	.54	.62	.78
Corr. of Logs	.58	.54	.57	.73	.75
Spearman	.62	.29	.58	.74	.75
Firm size controls	.19	.48	.44	.60	.59
N	706	321	4754	88	164

[a]Measured in millions of dollars of IT labor expenses. [b]Measured in millions of dollars of IT capital stock.
[c]Measured in number of IT employees. All correlations with multi-year samples include year dummies.

We also compare the behavior of these IT labor measures with that of CI data in the regression format that has been central to the IT productivity literature (e.g., Brynjolfsson and Hitt 1996; Dewan and Min 1997). We use Compustat data along with standard methods from the micro-productivity literature to compute other inputs. Table 3 compares estimates from productivity regressions using the CI data with estimates from productivity regressions using the labor measures of IT capital stocks. These regressions relate output to factor inputs using a growth framework, and are based on data from 1987-2000, a period in which a number of studies found evidence of IT driven productivity growth (Oliner and Sichel 2000; Stiroh 2002; Brynjolfsson and Hitt 2003). In column (1), we report estimates using the CI measures of IT capital stock. Estimates of the output elasticity of IT capital stock are consistent with those from existing studies that use these data (see e.g., Brynjolfsson and Hitt 2003). Column (2) reports estimates using labor-based measures of firm level IT capital stock. Although the estimates are higher than those from using the CI data, the sizes are consistent with Lichtenberg's estimates of the contribution of IT personnel to output (Lichtenberg 1995). Moreover, since in equilibrium, the marginal product of any factor input

should be equal to its factor share, the larger coefficients may simply capture the fact that the input quantities associated with our measures are twice that of the direct contribution of IT capital. This observation is consistent with the cost structure reported for typical large scale corporate IS projects (Brynjolfsson, Fitoussi, and Hitt 2006). Column (3) includes both IT measures.

Table 3. IT Productivity Regressions, 1987-2000

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	OLS	OLS	OLS	IV	FE	FE	OLS	OLS
IT Capital	.124		.102	.146	.004			
	(.014)**		(.015)**	(.067)**	(.007)			
IT Labor		.155	.121			.082	.124	.122
		(.021)**	(.020)**			(.010)**	(.039)***	(.039)***
IT Outsourcing								.047
								(.024)*
Controls	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year
N	4745	4745	4745	3075	3075	3075	2217	2217
R^2	.87	.87	.88	0.80	0.69	0.70	.85	.85
Robust standard errors shown in parentheses. ** p<.05. Regressions also include employment and capital.								

Column (4) uses the CI measures of IT capital stock as an instrumental variable to correct for sampling error in the worker-based measures that may be biasing coefficient estimates downward. The CI data are a valid instrument because the sources of error in our worker-based measures of IT capital stock, such as the sampling error described earlier in the paper, should be uncorrelated with sources of error in the CI data. Using the CI data as an instrument slightly raises the estimated output elasticity on the worker-based measure of IT capital stock (t=2.18). This increase in coefficient size is fairly small, and a Hausman test cannot reject the hypothesis that the coefficients are the same (t = 0.05). The small increase in the coefficient estimate, along with strong first stage regression results, suggest that the error variance in our worker-based measures of IT capital stock is reasonably small compared to the variance of the capital stock measure.

Columns (5) and (6) compare the results of a fixed-effects specification relating changes in output to changes in IT capital stock and other factor inputs, where different measures of IT capital stock are used in the two columns. In the first column, we use the CI firm level measures based on computer equipment. The output elasticity of IT capital in this specification is not significantly different from zero (t=0.57). Column (6) shows the coefficient estimates when we replace the CI-based IT capital stock

measure with logged IT workers. The estimate of the contribution of IT capital to output jumps considerably (t=8.2). One reason it is difficult to find evidence supporting IT productivity in short time differences is because of measurement error in the computer input, which is a more severe problem in longitudinal analyses than in cross-sections. In long differences, however, researchers have found it easier to provide evidence of IT-led productivity growth because averaging attenuates errors. Therefore, significant findings using our personnel based estimates in single year differences may reflect smaller measurement errors. Alternatively, evidence of positive returns to IT investment using computer equipment measures may show up primarily in long differences because it takes time for firms to install the accompanying organizational investments necessary to realize productive returns. Our IT labor based measures may simply be more highly correlated with these unobservable organizational inputs than investments in capital.

In Columns (7) and (8) we provide evidence that our results are not substantially changed by IT outsourcing. The estimates in (7) are virtually unchanged when including outsourcing directly into the regression in (8) on the sample of firms for which 2008 outsourcing data are available. Collectively, these results suggests that our IT labor measures are a sufficiently well behaved measure of IT capital stocks, and are superior in consistency and length than any other readily available IT data. In the next section, we describe how we use these data to separate IT-related intangible capital into prices and quantities.

Hall's Quantity Revelation Theorem

The creation of this IT panel allows us to estimate how IT-related intangible capital values were affected by the dot-com bust, and to recover quantities and prices of ITIC using an approach pioneered by Hall (2001). Hall argues that under assumptions of 1) competitive markets, 2) constant returns to scale production, and 3) full factor adjustment, the quantities and prices of capital can be recovered from the value of a firm's market securities. The main departure from the method described by Hall is that we use

as our dependent variable the component of market value correlated with IT investment. After separating ITIC assets into prices and quantities, we use the quantity data to estimate ITIC depreciation rates.

Estimation Framework

To estimate the market value of IT-related intangible capital, we use methods described in Brynjolfsson, Hitt, and Yang (BHY) (2002). BHY show that an estimating equation relating market value (V_{it}) to capital assets (K_{it}) and a systematic, omitted component of market value (M_{it}) can be written

(3) $$V_{it} = \propto_t + \sum_{j=1}^{J}(1+v_j^*)K_{j,it} + M_{it} + \varepsilon_{it}^{v}$$

In the absence of significant adjustment costs, the v^* vector depends on correlations between observed capital assets and the omitted component of market value. A high value for a particular capital asset in the market value equation implies a correlation between that asset and a component of the omitted value **M**, such as a large stock of intangible assets**.** This implies that $\boldsymbol{v^*}$ is the vector of coefficients that would arise in a regression of capital assets on the omitted market value component.

(4) $$M_t^I = \beta + \sum_{j=1}^{J} v_j K_{j,it} + \varepsilon_{it}^{M}$$

BHY use this framework along with data on computer investments to demonstrate associations between computer investments and market value. Estimates of the value of IT-related intangible capital can be created from observable computer asset values and the parameter estimates from (3) through the relationship

(5) $$\hat{v}_t^I = v_c^* K_{c,it}$$

where $K_{c,it}$ are computer asset values and v_c^* is the parameter estimate resulting from including computer assets in the regression in (4). This approach allows us to estimate IT-related intangible capital values in each firm-year.

Given a time-series progression of market values for ITIC, Hall's Quantity Revelation Theorem separates these values into quantity and a market-determined shadow price. Hall notes that the value of capital is the quantity times the price of installed capital.

(6) $$v_t^I = p_t^I q_t^I$$

where p_t^I and q_t^I are used to denote the prices and quantities of IT-related intangible capital, respectively, and v_t^I is the value of the IT-related intangible capital belonging to a firm. An additional restriction is set by adjustment costs and an investment optimization condition – value-optimizing firms invest in these IT-related intangibles until the marginal adjustment cost equals the difference between the installed price ratio and the acquisition price. That condition can be written

(7) $$(\alpha_t^I)\frac{q_t^I - q_{t-1}^I}{q_{t-1}^k} = p_t^I - 1$$

where following the approach outlined by Hall, we substitute physical capital q_{t-1}^k for ITIC in the denominator to avoid division by zero in early periods, and we take the adjustment technology to be quadratic with constant returns to scale. Therefore, given the market value of ITIC from (5) and assuming a value of 3.0 for the ITIC adjustment parameter α (see Hall 2002 for a justification of using this value for α and a sensitivity analysis), (6) and (7) are two equations in two unknowns, the quantity and shadow price of IT-related intangible capital. Recovering ITIC stocks in any period requires solving an equation that is quadratic in capital stocks. By setting initial values for ITIC, recursion through this system produces prices and quantities for IT-related intangible capital in each year for each firm. We set initial values of ITIC capital to zero, but Hall argues that this method is not sensitive to initial conditions, and later in this analysis, we test the sensitivity of our results to different values of the α parameter as well as to how the initial ITIC values are seeded.

Quantity estimates can then be used to estimate depreciation rates for ITIC. ITIC accumulation can be described using the perpetual inventory method

(8) $$q_t^I = \tau_t^I + (1 - \delta^I)q_{t-1}^I$$

where τ_t^I is investment into IT-related intangible capital at time *t* and δ^I is the fixed rate of depreciation of existing IT-related intangible capital. Although investments into ITIC are generally invisible to researchers, if the primary input into ITIC production is IT labor, the investment into units of ITIC is roughly proportional to the quantity of IT labor used in the firm. Therefore, an estimating equation for the depreciation of ITIC can be written

$$q_{i,t}^{I} - q_{i,t-1}^{I} = wL_{it}^{I} - \delta^{I} q_{i,t-1}^{I} + \varepsilon_{it} \tag{9}$$

where the parameter estimate on the number of IT workers includes a wage rate that relates one year of IT labor to the production of ITIC. The estimated coefficient on the lagged value of ITIC stock is the depreciation rate.

Results

Table 4 reports the results of regressions relating market value to IT and other inputs using the Tobin's q estimation framework described in (3). We report estimates using a Least Absolute Deviation (LAD) technique rather than conventional OLS for direct comparability with BHY and because it minimizes the impact of outliers and reduces the impact of firm heterogeneity on our estimates, but our results do not change substantially if OLS techniques are used. In Column (1), we replicate the results in BHY, using computer equipment based measures of IT capital stock. Estimates on Property, Plant, and Equipment (PPE) and other assets are close to their expected values. The coefficient estimate on IT capital suggests that a dollar invested in IT capital is associated with over 14 dollars in market value (t=71.3). Although the estimates in BHY associate a dollar of computer investment to only 11 dollars in market value, their study extends only through 1997, so higher estimates are consistent with the increases in technology company market values in the late 1990's. Column (2) includes estimates from regressions using the called IT-labor based measures. The estimates suggest similar amounts of intangible value from IT labor investment, and the estimates indicate that the firms for which our measures are available are not systematically different from firms in the BHY study.

Table 4. Regressions of Market Value on IT Inputs

	(1)	(2)	(3)	(4)	(5)
Years	1987-2000	1987-2000	1987-2006	2002-2006	2002-2006
	IT Capital	IT Labor (Sample Matched to IT Capital)	IT Labor, Full Sample	IT Labor, Outsourcing Sample	IT Labor with Outsourcing Controls
PP&E	1.27 (.007)***	1.22 (.008)**	1.32 (.002)**	1.29 (.048)***	1.27 (.058)***
Other Assets	1.08 (.002)***	1.03 (.002)**	1.09 (.000)**	1.18 (.039)***	1.21 (.047)***
IT Capital	14.1 (.597)***				
IT Labor		14.4 (.185)**	18.3 (.072)**	4.08 (2.10)*	5.34 (2.51)**
IT Outsourcing					-17.9 (16.4)
Controls	Industry Year	Industry Year	Industry Year	Industry Year	Industry Year
Observations	2845	2845	8292	260	260
Pseudo R^2	.56	.57	.69	.65	.65

Robust standard errors in parentheses. Least absolute deviation (LAD) estimates are reported. ** and * are significant at the 1% and 5% levels, respectively. Dependent variable is market value.

The regression in Column (3) includes a larger sample of firms, including many mid-market firms, and extends through 2006. The estimates in (3) indicate that more valuable IT-related intangible assets were developed over the longer sample. In the longer panel, a dollar of IT investment appears to be associated with closer to 18 dollars of value. In Columns (4) and (5) we report estimates from regressions that include 2008 IT outsourcing levels and we restrict the sample to the years from 2002-2006, because our IT outsourcing data become less accurate farther back in time. Column (4) shows results from the sample for which these outsourcing data are available, but does not include the IT outsourcing measure. After including the IT outsourcing measure in (5), the estimates are virtually unchanged.

To estimate the total value of IT-related intangible capital in each firm-year, we use estimates from a specification similar to the one shown in equation (4). Using these parameter estimates, we estimate IT-related intangible capital values as described in equation (5). Figure 1 illustrates how ITIC values have been changing over time, where the blue line represents the total value of the ITIC for the firms in our panel. The trend line suggests that the value that investors assign to ITIC has been increasing over time, and that both the dot-com bubble and bust had a strong effect on ITIC values. Given these ITIC

values, we can use Hall's approach to separate ITIC prices and quantities. Figure 2 and Figure 3 show how the price and quantity of IT-related intangible capital have been changing over time. The dominant feature in the average price trend line is the rise and fall in the price of ITIC corresponding to the late 1990's dot-com bubble. However, Figure 3 indicates only a steady accumulation of ITIC quantities, except for a brief slow down in the rate of growth after the dot-com bust. Therefore, the dot-com bust appears to have been associated with an adjustment in the price of ITIC, rather than its quantity. Figure 4 compares the growth in quantities of physical capital and ITIC for the firms in the panel. The trend lines indicate that by the end of our sample, ITIC quantities have grown to approximately a third that of physical capital.

Figure 1. ITIC Value

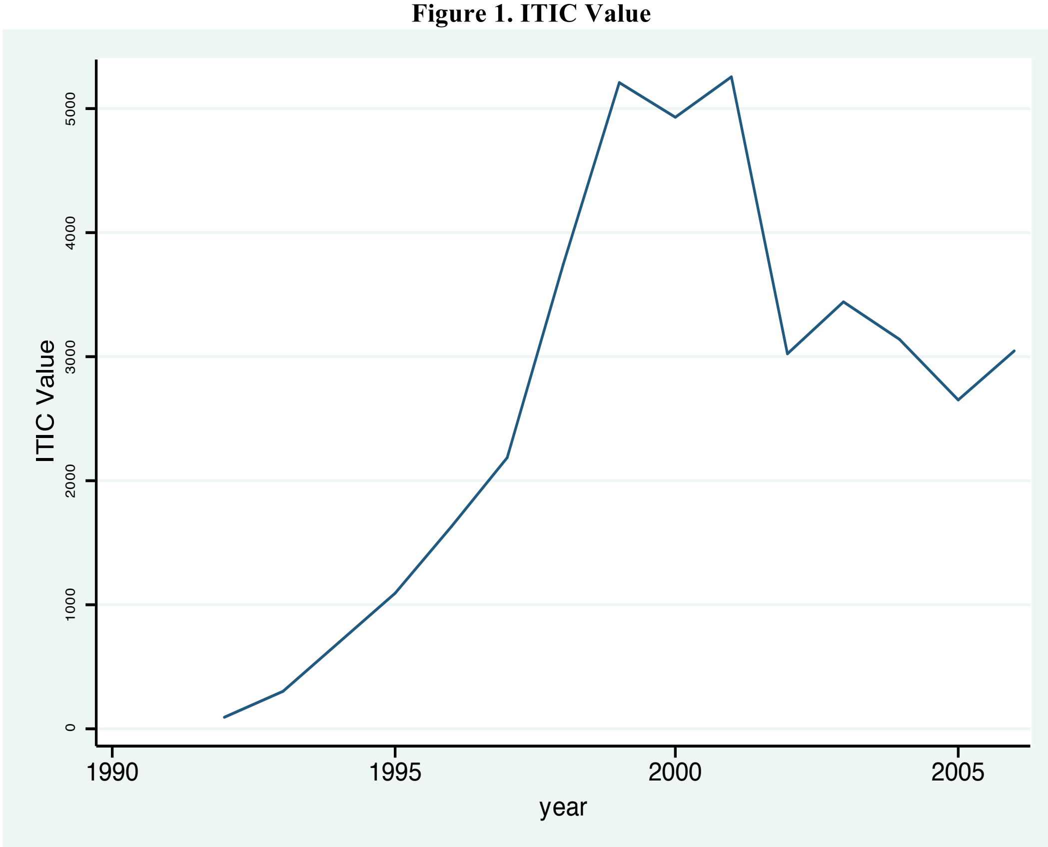


Figure 2. ITIC Price

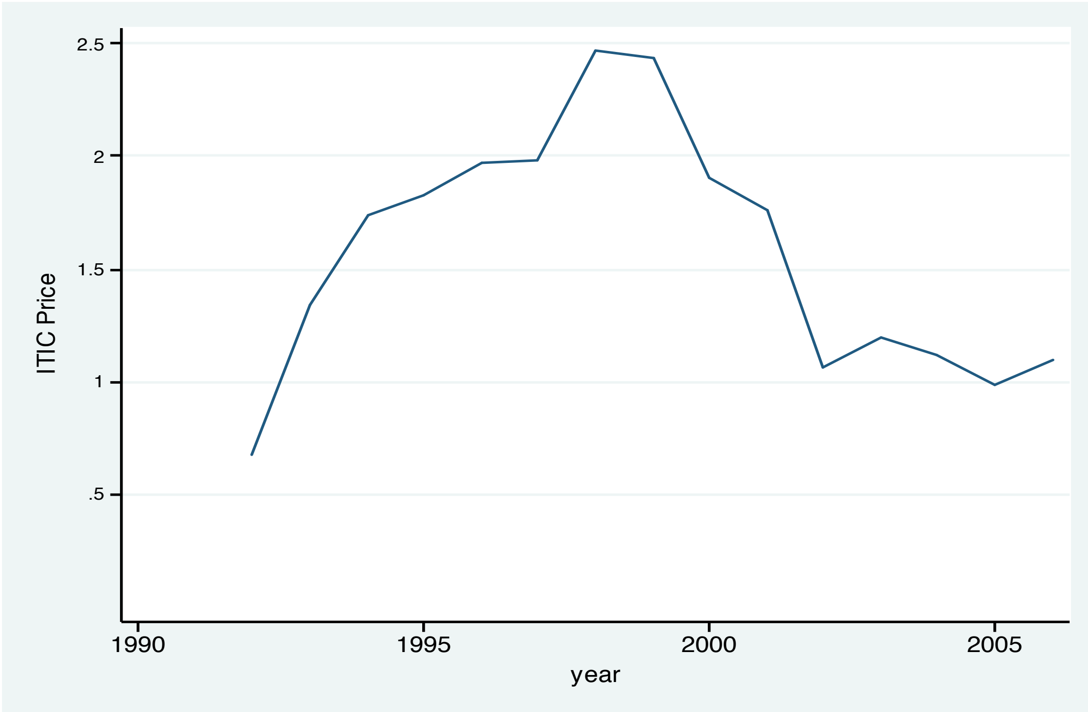


Figure 3. ITIC Quantities

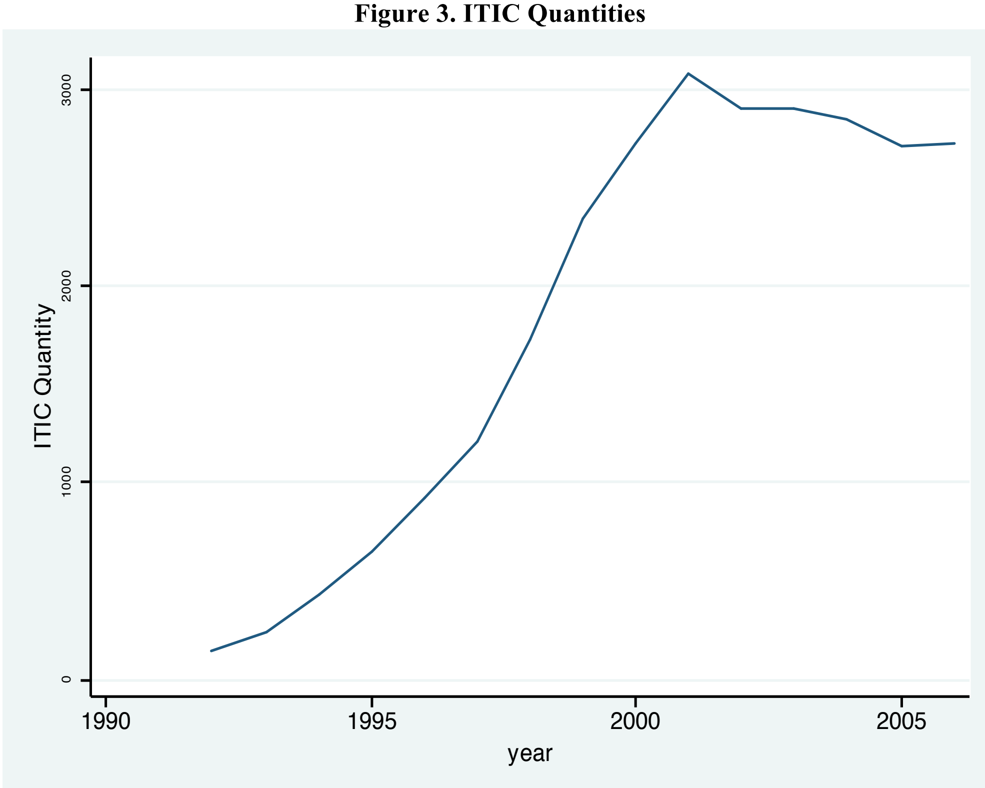
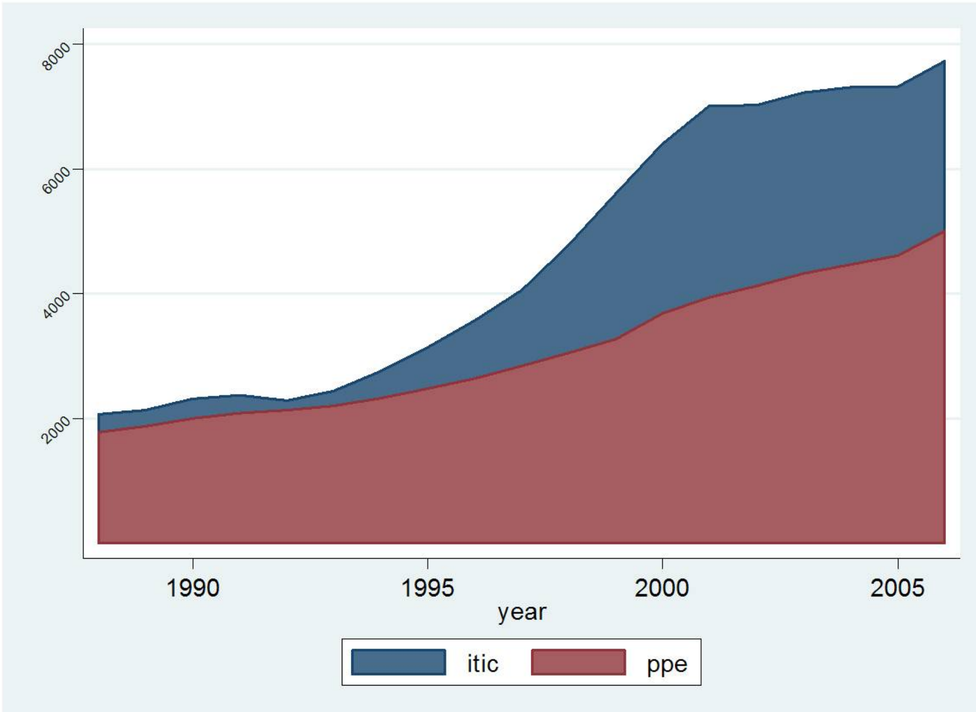


Figure 4. Physical Capital and ITIC



Finally, we estimate depreciation rates of IT-related intangible capital using the method described in equation (9). Table 5 shows estimated depreciation rates of IT-related intangible capital after 2000.

Table 5. Depreciation Rates for ITIC after 2000

	δ^{I}
No industry controls	.065** (.003)
1 digit industry controls	.068** (.004)
2 digit industry controls	.079** (.004)
Author's estimates based on estimates from specification in (9). Robust standard errors in parentheses. ** is significant at 1% level.	

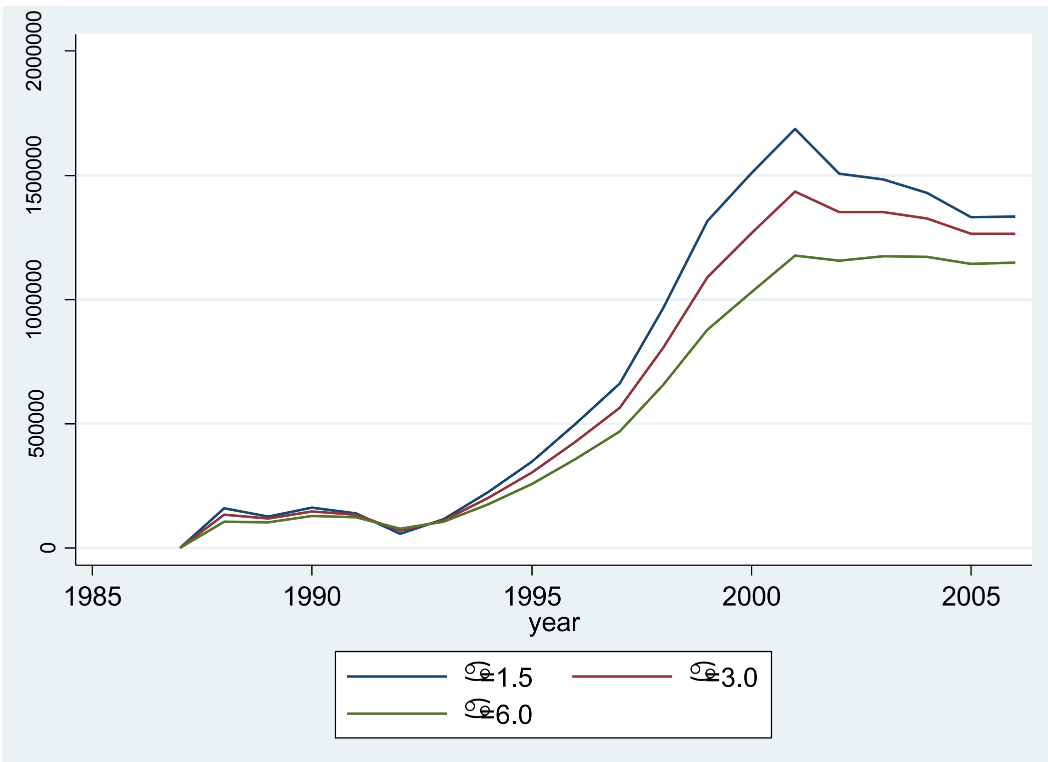
The first estimate includes depreciation rates for all firms without industry or year controls. This estimate, 6.5%, is significant (t=21.7), and is close to estimated depreciation rates for physical capital. Adding one-digit industry controls raises the depreciation estimate only slightly to 6.8% (t=17.0) but adding two-digit industry controls raises the depreciation estimates to about 7.9% (t=20.0). These values are close to the

depreciation rates for many types of physical capital, and close to Hall's parameter value of 6.0% that he chooses based on various sensitivity tests.

Robustness Tests

Figure 5 illustrates how quantities of ITIC evolve under different values for the adjustment cost parameter. Halving and doubling the α parameter shifts the estimated quantity curve up or down, but not its trajectory.[3]

Figure 5: Sensitivity to alpha values



In Figure 6, we test the robustness of the framework to assumptions about initial conditions. Rather than seeding 1987 values to zero, we randomly seed each firm with a quantity between zero and the average 1995 values of ITIC quantities, which addresses the concern that at the beginning of our sample, firms may already have developed significant quantities of ITIC. The curves in Figure 6 are consistent with

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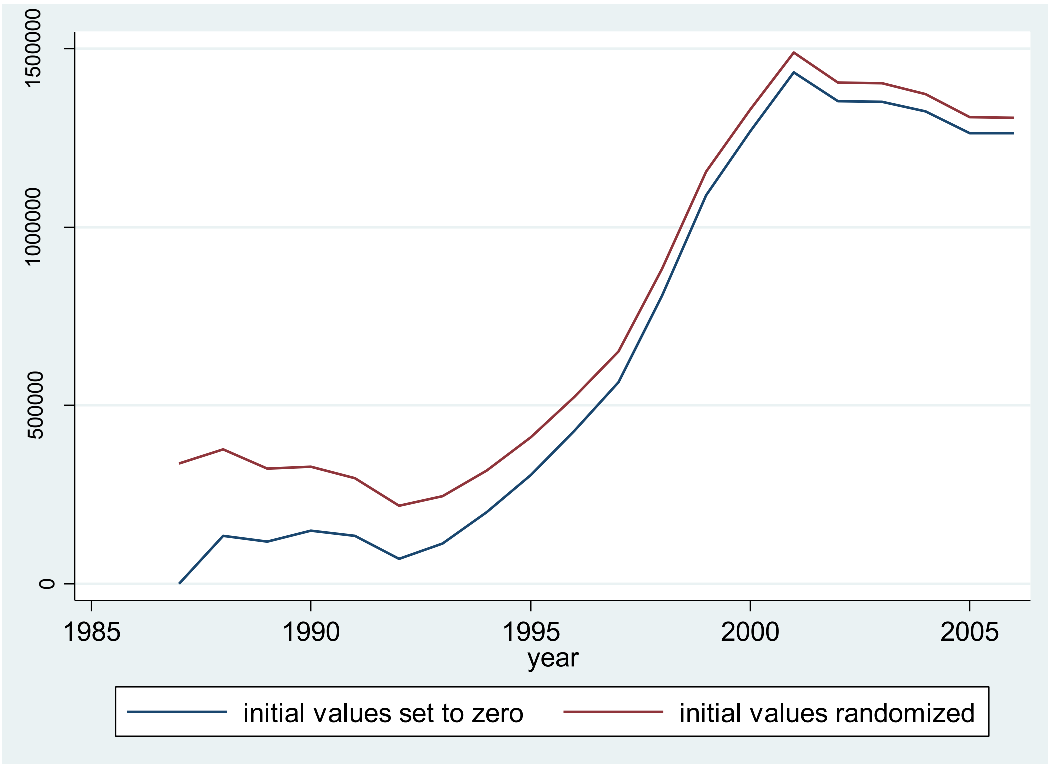
3 Hall provides further argument that an adjustment cost parameter of 1.5 or 6.0 would produce results inconsistent with economic behavior (Hall 2002).

Hall's assertion that assumptions about initial conditions do not have a large effect on later values due to the convergent nature of the process.

Figure 6: Sensitivity to Initial Conditions



Conclusions

This paper illustrates that although some of the recent changes in ITIC value are due to price fluctuations, firms continued to accumulate IT-related intangible capital after the dot-com bust. We find that by 2006, IT-related assets had grown to about one-third of the level of physical assets. Furthermore, low depreciation levels, similar to those of physical capital, indicate that firms are building these stocks significantly. If past relationships hold, this accumulation of intangible capital should fuel productivity growth in coming years. Our depreciation rate estimates are close to that of physical capital, and about half that of R&D capital (Nadiri and Prucha, 1997). Even if new investments in organizational complements were to cease, these depreciation estimates suggest it would take almost a decade to return to the ITIC levels present in the early 1990s.

These findings have implications for managers and for policymakers. For managers, our findings suggest that investment in these information structures produces long-lived, durable assets. Furthermore, our depreciation findings suggest how managers might efficiently allocate spending between the development of new information structures and the maintenance of existing information structures. For policy makers, these findings suggest that the large waves of investment in IT-related intangibles are associated with the development of significant productive capacity and, all else being equal, this should help boost long-run growth.

It should be noted that depreciation rates are principally measured during a time of economic expansion, raising the possibility that adverse economic conditions such as those during the 2008 recession could accelerate the depreciation of ITIC. Nonetheless, the fact that ITIC assets behave similarly to other capital assets in recent years is itself interesting. This may be because translating organizational innovations into productive capital requires significant investment in reengineering and skills. Thus, even if firms have the appropriate absorptive capacity, knowledge of how to construct IT-related intangible assets will not lead to productive ITIC any more than access to the blueprints of a competitor's plant will directly lead to productive capacity.

There are, however, some important differences between ITIC and physical assets that are worth noting. Unlike physical capital, ITIC has diminished value outside the context of the firm. This has important implications for firm valuation and acquisition, and suggests some interesting areas for future research. Development researchers have traditionally looked at capital accumulation as an engine for growth. The lack of secondary markets for IT-related intangible assets ties these questions together in an important way with to firm health. When firms are dismantled, ITIC may disappear. Thus, it may be interesting to explore the context-sensitivity and transferability of ITIC. For example, the movement of IT labor between firms may transfer innovations to new environments. It is worth understanding whether firms are capable of converting these flows of know-how and expertise into productive capital.

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