

**Paradox Lost?
Firm-level Evidence on the Returns to
Information Systems Spending**

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Paradox Lost?

Firm-level Evidence on the Returns to Information Systems Spending

ABSTRACT

The "productivity paradox" of information systems (IS) is that, despite enormous improvements in the underlying technology, the benefits of IS spending have not been found in aggregate output statistics. One explanation is that IS spending may lead to increases in product quality or variety which tend to be overlooked in aggregate output statistics, even if they increase sales at the firm-level. Furthermore, the restructuring and cost-cutting that are often necessary to realize the potential benefits of IS have only recently been undertaken in many firms.

Our study uses new firm-level data on several components of IS spending for 1987-1991. The dataset includes 367 large firms which generated approximately \$1.8 trillion dollars in output in 1991. We supplemented the IS data with data on other inputs, output, and price deflators from other sources. As a result, we could assess several econometric models of the contribution of IS to firm-level productivity.

Our results indicate that IS spending has made a substantial and statistically significant contribution to firm output. We find that the gross marginal product (MP) for computer capital averaged 81% for the firms in our sample. We find that the MP for computer capital is at least as large as the marginal product of other types of capital investment and that, dollar for dollar, IS labor spending generates at least as much output as spending on non-IS labor and expenses. Because the models we applied were similar to those that have been previously used to assess the contribution of IS and other factors of production, we attribute the different results to the fact that our data set is more current and larger than others explored. We conclude that the "productivity paradox" disappeared by 1991, at least in our sample of firms.

1. INTRODUCTION

Spending on information systems (IS), and in particular information technology (IT) capital, is widely regarded as having enormous potential for reducing costs and enhancing the competitiveness of American firms. Although spending has surged in the past decade, there is surprisingly little formal evidence linking it to higher productivity. Several studies, such as those by Loveman (1994) and by Barua, Kriebel & Mukhopadhyay (1991) have been unable to reject the hypothesis that computers add nothing at all to total output, while others estimate that the marginal benefits are less than the marginal costs (Morrison and Berndt 1990).

This "productivity paradox" has alarmed managers and puzzled researchers. American corporations have spent billions of dollars on computers and many firms have radically restructured their business processes to take advantage of computers. If these investments have not increased the value produced or reduced costs, then management must rethink their IS strategies. Roach (1987), who was among the first to identify the productivity shortfall in the 1980s, is currently more optimistic about the current prospects for productivity growth because many firms have finally begun to realize the potential labor savings enabled by IT. However, because none of the previous estimates of IT productivity were based on recent data, this hypothesis remains untested.

This study considers new evidence and finds sharply different results from previous studies. Our dataset is based on five annual surveys of several hundred large firms for a total of 1121 observations¹ over the period 1987-1991. The firms in our sample generated approximately \$1.8 trillion dollars worth of gross output in the United States in 1991, and their value-added of \$630 billion accounted for about 13% of the 1991 US gross domestic product of \$4.86 trillion (Council of Economic Advisors, 1992). Because the identity of each of the participating firms is known, we were able to supplement the IS data with data from several other sources. As a result, we could assess several econometric models of the contribution of IS to firm-level productivity.

Our examination of these data indicates that IS spending has made a substantial and statistically significant contribution to the output of firms. Our point estimates indicate that, dollar for dollar, spending on computer capital created more value than spending on other types of capital. We find that the contribution of IS to output does not vary much across

¹ An observation is one year of data on all variables for a specific firm. We did not have all five years of data for every firm, but the data set does include at least one year of data for 367 different firms.

years, although there is weak evidence of a decrease over time. We also find some evidence of differences across various sectors of the economy. Technology strategy also appears to affect returns. For instance, we find that neither firms that relied heavily on mainframes nor firms which emphasized personal computer (PC) usage performed as well as firms that invested in a mix of mainframes and PCs.

In each of the specifications we examine, estimates of the gross marginal product for computers exceeds 50% annually. Considering a 95% confidence interval around our estimates, we can reject the hypothesis that computers add nothing to total output. Furthermore, several of our regressions suggest that the marginal product for computers is significantly higher than the return on investment for other types of capital, although this comparison is dependent on the assumed cost of computer capital. Overall, our findings suggest that for our sample of large firms, the "productivity paradox" disappeared in the 1987-1991 period.

1.1 Previous research on IT and productivity

There is a broad literature on IT value which has been recently reviewed in detail elsewhere (Brynjolfsson 1993; Wilson 1993). Many of these studies examined correlations between IT spending ratios and various performance measures, such as profits or stock returns (Dos Santos *et al.* 1993; Harris and Katz 1988; Strassmann 1990), and some found that the correlation was either zero or very low, which has led to the conclusion that computer investment has been unproductive. However, in interpreting these findings, it is important to bear in mind that economic theory predicts that in equilibrium, companies that spend more on computers would not, on average, have higher profitability or stock market returns. Managers should be as likely to over-spend as to under-spend, so high spending should not necessarily be "better". Where correlations are found, they should be interpreted as indicating either an *unexpectedly* high or low contribution of information technology, as compared to the performance that was anticipated when the investments were made. Thus, perhaps counter-intuitively, the common finding of zero or weak correlations between the percentage of spending allocated to IT and profitability do not necessarily indicate a low payoff for computers.

To examine the contribution of IT to output, it is helpful to work within the well-defined framework of the economic theory of production. In fact, Alpar & Kim (1990) found that methods based on production theory could yield insights that were not apparent when more loosely constrained statistical analyses were performed. The economic theory of production posits that the output of a firm is related to its inputs via a production function and predicts that each input should make a positive contribution to output. A further prediction of the theory is that the marginal cost of each input should just equal the marginal benefit produced by that input. Hundreds of studies have estimated production functions with various inputs, and the predictions of economic theory have generally been confirmed (See Berndt, 1991, especially chapters 3 and 9, for an excellent review of many of these studies).

The "productivity paradox" of IT is most accurately linked to a subset of studies based on the theory of production which either found no positive correlation overall (Barua *et al.* 1991; Loveman 1994), or found that benefits fell short of costs (Morrison and Berndt 1990). Using the Management of the Productivity of Information Technology (MPIT) database,² Loveman (1994) concluded: "Investments in IT showed no net contribution to total output". While his elasticity estimates ranged from -.12 to .09, most were not statistically distinguishable from zero. Barua, Kriebel and Mukhpadhyay (1991) found that computer investments are not significantly correlated with increases in return on assets. Similarly, Morrison and Berndt (1990) examined industry-level data using a production function that controlled for changes in other inputs and found that each dollar spent on "high tech" capital³ increased measured output by only 80 cents on the margin.

Although previous work provides little econometric evidence that computers improve productivity, Brynjolfsson's (1993) review of the overall literature on this "productivity paradox" concludes that the "shortfall of evidence is not necessarily evidence of a shortfall." He notes that increases in product variety and quality should properly be

² The database contains standard financial information, IT spending data and other economic measures such as product prices and quality for 60 business units of 20 firms over the period 1978-1984. See Loveman (1994) for a more detailed description.

³ The precise definition of "IT" varies from study to study. Morrison and Berndt included scientific instruments, communications equipment, photocopiers and other office equipment as well as computers in their definition. Others define IT even more broadly, including software, services and related peripheral equipment. As described in section 2.3 below, the definition used in our study is fairly narrow and includes separate estimates for the effect of corporate computer capital and corporate IS labor.

counted as part of the value of output, but that the price deflators that the government currently uses to remove the effects of inflation are imperfect. These deflators are computed assuming that quality and other intangible characteristics do not change for most goods. As a result, inflation is overestimated and real output is underestimated by an equivalent amount (because real output is estimated by multiplying nominal output by the price deflator). In addition, as with any new technology, a period of learning, adjustment and restructuring may be necessary to reap its full benefits, so that early returns may not be representative of the ultimate value of IT. Accordingly, he argues that "mismeasurement" and "lags" are two of four viable explanations (along with "redistribution" and "mismanagement") for the collected findings of earlier studies. This leaves the question of computer productivity open to continuing debate.

1.2 Data Issues

The measurement problem has been exacerbated by weaknesses in available data. Industry-level output statistics have historically been the only data that are available for a broad cross-section of the economy. In a related study using much of the same data as the Morrison & Berndt (1990) study, Berndt and Morrison (1994) conclude, "...there is a statistically significant negative relationship between productivity growth and the high-tech intensity of the capital." However, they also point out: "it is possible that the negative productivity results are due to measurement problems...". Part of the difficulty is that industry-level data does not allow us to distinguish firms *within* a particular industry which invest heavily in IT from those with low IT investments. Comparisons can only be made among industries, yet these comparisons can be sensitive to price deflators used, which in turn depend on the assumptions about how much quality improvement has occurred in each industry. Firm-level production functions, on the other hand, will better reflect the "true" outputs of the firm, insofar as the increased sales at each firm can be directly linked to its use of computers and other inputs, and all the firms are subject to the same industry-level price deflator.

On the other hand, a weakness of firm-level data is that it can be painstaking to collect, and therefore, studies with firm level data have historically focused on relatively narrow samples. This has made it difficult to draw generalizable results from these studies. For instance, Weill (1992) found some positive impacts for investments in some categories of

IS but not for overall IS spending. However, the 33 strategic business units (SBUs) in his sample from the valve manufacturing industry accounted for less than \$2 billion in total sales, and he notes, "The findings of the study have limited external validity." (Weill, 1992). By the same token, the Loveman (1994) and Barua, Kriebel and Mukhudpadhyay (1991) studies were based on data from only 20 firms (60 SBUs) in the 1978-82 period and derived only rather imprecise estimates of IT's relationship to firm performance.

The imprecision of previous estimates highlights an inherent difficulty of measuring the benefits of IT investment. To better understand the perceived benefits, we conducted a survey of managers to find out the relative importance of reasons for investing in IT.⁴ Our results indicate that the primary reason for IT investment was customer service, followed by cost savings. Close behind were timeliness and quality. In practice, the value of many of the benefits of IT, other than cost savings, are not well captured in aggregate price deflators or output statistics.⁵

Given the weaknesses of existing data, it has been very difficult to distinguish the contribution of IT from random shocks that affect productivity even when sophisticated analytical methods are applied. As Simon (1984) has observed:

In the physical sciences, when errors of measurement and other noise are found to be of the same order of magnitude as the phenomena under study, the response is not to try to squeeze more information out of the data by statistical means; it is instead to find techniques for observing the phenomena at a higher level of resolution. The corresponding strategy for economics is obvious: to secure new kinds of data at the micro level.

A convincing assessment of IS productivity would ideally employ a sample which included a large share of the economy (as in the Berndt and Morrison studies), but at a level of detail that disaggregated inputs and outputs for individual firms (as in Loveman (1994), Barua et al. (1991), and Weill (1992)). Furthermore, because the recent restructuring of many firms may have been essential to realizing the benefits of IS spending, the data should be as current as possible. Lack of such detailed data has hampered previous efforts. While our

⁴ Further detail on the survey results is given in Brynjolfsson (1994).

⁵ No good methodology exists for incorporating some of the other benefits, such as variety. Baily and Gordon (1988) estimate that "true" annual productivity growth might be as much as 0.5% higher overall than reported in official statistics that do not account for most intangible benefits.

paper applies essentially the same models as those used in earlier studies, we use new, firm-level data which is more recent, more detailed and includes more companies. We believe this accounts for our sharply different results.

1.3 Theoretical Issues

As discussed above, there are a number of hypotheses for explaining the productivity paradox, including the possibility that it is an artifact of mismeasurement. We consider this possibility in this paper.

More formally, we examine the following hypotheses using a variety of statistical tests:

- H1) The output contributions of computer capital and IS staff labor are positive;
- H2) The net output contributions of computer capital and IS staff labor are positive after accounting for depreciation and labor expense respectively.

In our analysis, we build on a long research stream which applies production theory to determine the contributions of various inputs to output.⁶ This approach uses economic theory to determine the set of relevant variables and to define the structural relationships among them. The relationship can then be estimated econometrically and compared with the predictions of economic theory. In particular, for any given set of inputs, the maximum amount of output that can be produced, according to the known laws of nature and existing "technology", is determined by a *production function*. As noted by Berndt (1991), various combinations of inputs can be used to produce a given level of output, so a production function can be thought of as pages of a book containing alternative blueprints. This is essentially an engineering definition, but business implications can be drawn by adding an assumption about how firms behave, such as profit maximization or cost minimization. Under either assumption, no inputs will be "wasted", so the only way to increase output for a given production function is to increase at least one input.

The theory of production not only posits a relationship among inputs and output, but also posits that this relationship may vary depending on particular circumstances. Many of

⁶ (Berndt 1991) lists over a hundred references on this approach and presents an excellent literature review.

these differences can be explicitly modeled by a sufficiently general production function without adding additional variables. For instance, it is common to assume that there are constant returns to scale, but more general models will allow for increasing or decreasing returns to scale. In this way, it is possible to see whether large firms are more or less efficient than smaller firms. Other differences may have to do with the economic environment surrounding the firm, and are not directly related to inputs. Such differences are properly modeled as additional "control" variables. Depending on prices and desired levels of output, different firms may choose different combinations of inputs and outputs, but they will all adhere to the set defined by their production function. The neoclassical economic theory of production has been fairly successful empirically, despite the fact that it treats firms as "black boxes" and thus ignores history or details of the internal organization of firms. Of course, in the real world, such factors can make a significant difference and recent advances in the theory of the firm may enable them to be more rigorously modeled as well.

To operationalize the theory for our sample, we assume that the firms in our sample produce a quantity of OUTPUT (Q) via a production function (F), whose inputs are COMPUTER CAPITAL (C), NON-COMPUTER CAPITAL (K), IS STAFF labor (S), and OTHER LABOR AND EXPENSES (L).⁷ These inputs comprise the sum total of all spending by the firm and all capitalized investment. Economists historically have not distinguished computer capital from other capital, lumping them together as a single variable. Similarly, previous estimates of production functions have not distinguished IS staff labor from other types of labor and expenses. However, for our purposes, making this distinction will allow us to directly examine hypotheses such as H1 and H2 above. We seek to allow for fairly general types of influences by allowing for any type of environmental factors which affect the business sector (j) in which the company operates and year (t) in which the observation was made.^{8,9} Thus, we can write:

⁷ Another common way to operationalize the theory is to use the production function to derive a "cost function" which provides the minimum cost required for a given level of output. While cost functions have some attractive features, they require access to firm-level price information for each input, which are data we do not have.

⁸ A more complete model might include, in addition to these controls, other variables which may affect output such as the organization's maturity in the use of IT or the degree of restructuring it has undergone. We hope to explore such models in future research.

⁹ Lags of IT spending could also be incorporated into the production function. For our purposes we chose not to because lagged spending is already included in IT capital stock, and the data set is too short to get reasonable estimates of a more general lag structure.

$$Q = F(C, K, S, L; j, t) \quad (1)$$

Output and each of the input variables can be measured in either physical units or dollars. If measured in dollar terms, the results will more closely reflect the ultimate objective of the firm (profits, or revenues less costs). However, this approach requires the deduction of inflation from the different inputs and outputs over time and in different industries. This can be done by multiplying the nominal dollar value of each variable in each year by an associated deflator to get the real dollar values. Unfortunately, as mentioned earlier, this approach will probably underestimate changes in product quality or variety since the deflators are imperfect.

The amount of output that can be produced for a given unit of a given input is often measured as the marginal product (MP) of the input, which can be interpreted as a rate of return. When examining differences in the returns of a factor across firms or time periods, it is important to control for the effects of changes in the other inputs to production. Since the production function identifies both the relevant variables of interest as well as the controls, the standard approach to conducting productivity analyses is to assume that the production function, F , has some functional form, and then estimate its parameters (Berndt, 1991, pp. 449-460).

The economic theory of production places certain technical constraints on the choice of functional form, such as quasi-concavity and monotonicity (Varian 1992). In addition, we observe that firms use multiple inputs in production, so the functional form should also include the flexibility to allow continuous adjustment between inputs as the relative prices of inputs change.¹⁰ Perhaps the simplest functional form that relates inputs to outputs and is consistent with these constraints is the Cobb-Douglas specification, variants of which have been used since 1896 (Berndt, 1991). This specification is probably the most common functional form used for estimating production functions and remains the standard

¹⁰ For instance, a simple linear relationship between inputs and outputs is ruled out by these constraints. A linear production function implies that a firm will either use only the lowest cost input, or an indeterminate mix of all inputs if the prices are exactly the same.

for studies such as ours, which seek to account for output growth by looking at inputs and other factors.¹¹

$$Q = e^{\beta_0} C^{\beta_1} K^{\beta_2} S^{\beta_3} L^{\beta_4} \quad (2)$$

In this specification, β_1 and β_3 are the output elasticity of COMPUTER CAPITAL and information systems staff (IS STAFF), respectively.¹² If the coefficients $\beta_0 - \beta_4$ sum to 1, then the production function exhibits constant returns to scale. However, increasing or decreasing returns to scale can also be modeled with the above function. The principal restriction implied by the Cobb-Douglas form is that the elasticity of substitution between factors is constrained to be equal to -1. This means that as the relative price of a particular input increases, the amount of the input employed will decrease by a proportionate amount, and the quantities of other inputs will increase to maintain the same level of output. As a result, this formulation is not appropriate for determining whether inputs are substitutes or complements.

The remainder of the paper is organized as follows: in section 2, we describe the statistical methodology and data of our study. The results are presented in section 3. In section 4, we conclude with a discussion of the implications of our results.

2. METHODS AND DATA

2.1 Estimating Procedures

The basic Cobb-Douglas specification is obviously not linear in its parameters. However, by taking logarithms of equation (2) and adding an error term (ϵ), one can derive an

¹¹ For instance, Hall (1993) introduces her Cobb-Douglas production function with the words: "...using the by now standard growth accounting framework...".

¹² Formally, the output elasticity of computers, E_C , is defined as: $E_C = \frac{\partial F}{\partial C} \frac{C}{F}$. For our production function, F, this reduces to: $E_C = \beta_1 e^{\beta_0} C^{\beta_1-1} K^{\beta_2} S^{\beta_3} L^{\beta_4} \frac{C}{e^{\beta_0} C^{\beta_1} K^{\beta_2} S^{\beta_3} L^{\beta_4}} = \beta_1$. The MP for computers is simply

the output elasticity multiplied by the ratio of output to computer input: $MP_C = \frac{\partial F}{\partial C} = \frac{\partial F}{\partial C} \frac{CF}{FC} = E_C \frac{F}{C}$

equivalent equation that can be estimated by linear regression. For estimation, we have organized the equations as a system of five equations, one for each year:

$$\text{Log } Q_{i,87} = \beta_{87} + \beta_j + \beta_1 \text{Log } C_{i,87} + \beta_2 \text{Log } K_{i,87} + \beta_3 \text{Log } S_{i,87} + \beta_4 \text{Log } L_{i,87} + \varepsilon_{87} \quad (3a)$$

$$\text{Log } Q_{i,88} = \beta_{88} + \beta_j + \beta_1 \text{Log } C_{i,88} + \beta_2 \text{Log } K_{i,88} + \beta_3 \text{Log } S_{i,88} + \beta_4 \text{Log } L_{i,88} + \varepsilon_{88} \quad (3b)$$

$$\text{Log } Q_{i,89} = \beta_{89} + \beta_j + \beta_1 \text{Log } C_{i,89} + \beta_2 \text{Log } K_{i,89} + \beta_3 \text{Log } S_{i,89} + \beta_4 \text{Log } L_{i,89} + \varepsilon_{89} \quad (3c)$$

$$\text{Log } Q_{i,90} = \beta_{90} + \beta_j + \beta_1 \text{Log } C_{i,90} + \beta_2 \text{Log } K_{i,90} + \beta_3 \text{Log } S_{i,90} + \beta_4 \text{Log } L_{i,90} + \varepsilon_{90} \quad (3d)$$

$$\text{Log } Q_{i,91} = \beta_{91} + \beta_j + \beta_1 \text{Log } C_{i,91} + \beta_2 \text{Log } K_{i,91} + \beta_3 \text{Log } S_{i,91} + \beta_4 \text{Log } L_{i,91} + \varepsilon_{91} \quad (3e)$$

where: Q, C, K, S, L and β_1 - β_4 are as before

87, 88, 89, 90 and 91 index each year

j indexes each sector of the economy, and

i indexes each firm in the sample

While each individual equation is based on a cross-section of the data, by constraining the coefficients on each factor to be equivalent in different years, time series variation in the data will also be reflected in the estimates of the system as a whole. In fact, under the assumption that the error terms in each equation are independently and identically distributed, estimating this system of equations is equivalent to pooling the data and estimating the parameters by ordinary least squares (OLS). However, it is likely that the variance of the error term varies across years, and that there is some correlation between the error terms across years. It is therefore possible to get more efficient estimates of the parameters by using the technique of Iterated Seemingly Unrelated Regressions (ISUR).¹³

As equations (3a) - (3e) are written, we have imposed the usual restriction that the parameters are equal across the sample, which allows the most precise estimates of the parameter values. We can also allow some or all of the parameters to vary over time or by firm characteristics, although this additional information is generally obtained at the expense of lowering the precision of the estimates. We will explore some of these

¹³ Sometimes also called IZEF, the iterated version of Zellner's efficient estimator, ISUR yields estimates that are numerically equivalent to the maximum likelihood estimator (Berndt, 1991). The ISUR procedure starts by estimating the coefficients by OLS to obtain an initial estimate of the error term covariance matrix, and then iteratively refines this estimate until convergence is reached at minimum error. This procedure implicitly corrects for serial correlation among the variables even when there are missing observations for some firms in some years. More traditional methods of correcting for serial correlation in panel data sets (Kmenta 1986) require complete data and do not perform well with short time dimensions.

alternative specifications in the results section; however, the main results of this paper are based on the system of equations shown in (3a)-(3e).

2.2 Data Sources and Variable Construction

This study employs a unique data set on IS spending by large U.S. firms which was compiled by International Data Group (IDG). The information is collected in an annual survey of IS managers at large firms¹⁴ that has been conducted since 1987. Respondents are asked to provide the market value of central processors (mainframes, minicomputers, supercomputers) used by the firm in the U.S., the total central IS budget, the percentage of the IS budget devoted to labor expenses, the number of PCs and terminals in use, and other IT related information.

Since the names of the firms are known and most of them are publicly traded, the IS spending information from the IDG survey could be matched to Standard and Poors' Compustat II¹⁵ to obtain measures of output, capital investment, expenses, number of employees and industry classification. In addition, these data were also combined with price deflators for output, capital, employment costs, expenses and IT capital.

There is some discretion as to how the years are matched between the survey and Compustat. The survey is completed at the end of the year for data for the following year. Since we are primarily interested in the value of computer capital stock, and the survey is timed to be completed by the beginning of the new fiscal year, we interpret the survey data as a beginning of period value, which we then match to the end of year data on Compustat (for the previous period). This also allows us to make maximum use of the survey data and is the same approach used by IDG for their reports based on these data (e.g. Maglitta and Sullivan-Trainor, 1991).¹⁶

¹⁴Specifically, the survey targets Fortune 500 manufacturing and Fortune 500 service firms that are in the top half of their industry by sales (see Table 2a).

¹⁵Compustat II provides financial and other related information for publicly traded firms, primarily obtained through annual reports and regulatory filings.

¹⁶This matching procedure may be sensitive to possible reverse causality between output and IS Labor as is shown by our Hausman test in table 6.

IDG reports the "market value of central processors" (supercomputers, mainframes and minicomputers) but only the total number of "PCs and terminals". Therefore, the variable for COMPUTER CAPITAL was obtained by adding the "market value of central processors" to an estimate of the value of PCs and terminals, which was computed by multiplying the weighted average value for PCs and terminals by the number of PCs and terminals.¹⁷ This approach yields roughly equal values, in aggregate, for central processors (\$33.0 Bn) as for PCs and terminals (\$30.4 Bn) in 1991. These values were corroborated by a separate survey by International Data Corporation (IDC 1991) which tabulates shipments of computer equipment by category. This aggregate computer capital is then deflated by the computer systems deflator reported in Gordon (1993).

The variables for IS STAFF, NON-IS LABOR AND EXPENSE and OUTPUT were computed by multiplying the relevant quantity from the IDG survey or Compustat by an appropriate government price deflator. IS STAFF was computed by multiplying the IS Budget figure from the IDC survey by the "percentage of the IS budget devoted to labor expenses...", and deflating this figure. NON-IS LABOR AND EXPENSE was computed by deflating total expense and subtracting deflated IS STAFF from this value. Thus, all the expenses of a firm are allocated to either IS STAFF or NON-IS LABOR AND EXPENSE.

Total capital for each firm was computed from book value of capital stock, adjusted for inflation by assuming that all investment was made at a calculated average age (total depreciation/current depreciation) of the capital stock.¹⁸ From this total capital figure, we subtract the deflated value of COMPUTER CAPITAL to get NON-COMPUTER CAPITAL. Thus, all capital of a firm is allocated to either COMPUTER CAPITAL or NON-COMPUTER CAPITAL. The approach to constructing total capital follows the methods used by other authors who have studied the marginal product of specific production factors using a similar methodology (Hall, 1990; Mairesse & Hall, 1993).

¹⁷ Specifically, we estimated the value of terminals and the value of PCs and then weighted them by the proportion of PCs versus terminals. For terminals, we estimated the value as the average list price of an IBM 3151 terminal in 1989 which is \$609 (Pelaia 1993). For PCs we used the average nominal PC cost over 1989-1991 of \$4,447, as reported in Berndt & Griliches (1990). These figures were then weighted by the proportion of PCs to terminals in the 1993 IDG survey (58% terminals). The resulting estimate was $.42 * \$609 + .58 * \$4,447 = \$2,835$.

¹⁸ An alternative measure of capital stock was computed by converting historical capital investment data into a capital stock using the Winfrey S-3 table. This approach was used in earlier versions of this paper (Brynjolfsson and Hitt 1993), with similar results. However, the calculation shown above is more consistent with previous research (see e.g. (Hall, 1993)).

The firms in this sample are quite large. Their average sales over the sample period were nearly \$7.4 billion. However, in many other respects, they are fairly representative of the US economy as a whole. For instance, their computer capital stock averages just over 2% of total sales, or about \$155 million, which is roughly consistent with the capital flow tables for the US economy published by the Bureau of Economic Analysis. Similarly, the average IS budget as a share of sales was very close to the figure reported in a distinct survey by CSC/Index (Quinn *et al.* 1993). A summary of the sources, construction procedure and deflator for each variable is provided in Table 1, and sample statistics are shown in Tables 2a and 2b.

2.3 Potential Data Problems

There are a number of possible errors in the data, either as a result of errors in source data or inaccuracies introduced by the data construction methods employed. First, the IDG data on IS spending are largely self-reported and therefore the accuracy depends on the diligence of the respondents. Some data elements require a degree of judgment -- particularly the market value of central processors and the total number of PCs and terminals. Also, not all companies responded to the survey, and even those that did respond in one year may not have responded in every other year. This may result in sample selection bias. For instance, high performing firms (or perhaps low performing firms) may have been more interested in participating in the survey.

However, the effect of the potential errors discussed above will probably be small. The information is reasonably consistent from year to year for the same firm, and we have checked the aggregate values against other independent sources. We used a different, independent source (Compustat) for our output measures and for our non-IT variables eliminating the chance of respondent bias for these measures. We also examined whether the performance of the firms in our sample (as measured by return on equity (ROE)) differ from the population of the largest half of Fortune 500 Manufacturing and Fortune 500 Service firms. Our results indicate that there are no statistically significant differences between the ROE of firms in our sample and those that are not (t-statistic = .7), which suggests that our sample is not disproportionately comprised of "strong" or "weak" firms. Furthermore, the average size of the firms of our sample is not significantly different from

the average size of firms in the top half of the Fortune 500 listings (t-statistic=.8). Finally, the response rate of the sample is relatively high at over 75%, suggesting that sample selection bias is probably not driving the results.

Second, there are a number of reasons why IS STAFF and COMPUTER CAPITAL may be understated, although by construction these errors do not reduce total capital and total expense for the firm. The survey is restricted to central IS spending in the US plus PCs and terminals both inside and outside the central department. Some firms may have significant expenditures on information systems outside the central department or outside the US. In addition, the narrow definitions of IS spending employed in this study may exclude significant costs that could be legitimately counted as COMPUTER CAPITAL such as software and communication networks. Furthermore, by including only the labor portion of IS expenses in IS STAFF as a separate variable (in order to prevent double counting of capital expenditure), other parts of the IS budget are left in the NON-IS LABOR AND EXPENSE category. The effects of these problems on the final results are discussed in the Results section, especially section 3.4.

A third area of potential inaccuracy comes from the price deflators. Numerous authors (Baily & Gordon, 1988; Siegel & Griliches, 1991) have criticized the current methods employed by the BEA for constructing industry-level price deflators. It has been argued that these methods substantially underestimate quality change or other intangible product improvements. If consumer purchases are in part affected by intangible quality improvements, the use of firm level data should provide a closer approximation to the true output of a firm, because firms which provide quality improvement will have higher sales and can be directly compared to firms in the same industry.

Finally, the measurement of OUTPUT and COMPUTER CAPITAL input in certain service industries appeared particularly troublesome. For financial services, we found that OUTPUT was poorly predicted in our model, presumably because of problems in defining and quantifying the output of financial institutions. In the telecommunications industry, it has been argued (Popkin 1992) that many of the productivity gains have come from very large investments in computer-based telephone switching gear, which is primarily classified as communications equipment and not COMPUTER CAPITAL, although it may be highly

correlated with measured computer capital. We therefore excluded all firms in the financial services industries (SIC60 - SIC69), and telecommunications (SIC48).¹⁹

3. RESULTS

3.1 Basic results

The basic estimates for this study are obtained by estimating the system of equations (3a)-(3e) by ISUR (see section 2.1). Note that we allow the intercept term to vary across sectors and years.

As reported in column 1 of Table 3, our estimate of β_1 indicates that COMPUTER CAPITAL is correlated with a statistically significant increase in OUTPUT. Specifically, we estimate that the elasticity of output for COMPUTER CAPITAL is 0.0169 when all the other inputs are held constant. Because COMPUTER CAPITAL accounted for an average of 2.09% of the value of output each year, this implies a gross MP (increase in dollar output per dollar of capital stock) for COMPUTER CAPITAL of approximately 81% per year.²⁰ In other words, an additional dollar of computer capital stock is associated with an increase in output of 81 cents per year on the margin.²¹

The estimate for the output elasticity for IS STAFF was 0.0178, which indicates that each dollar spent here is associated with a marginal increase in OUTPUT of \$2.62. The surprisingly high return to information systems labor may reflect systematic differences in human capital,²² since IS staff are likely to have more education than other workers. The high return may partially explain Krueger's (1991) finding that workers who use computers are paid a wage premium.

¹⁹ The impact of these changes in both cases was to lower the return to COMPUTER CAPITAL slightly as compared to the results on the full sample.

²⁰ As noted in footnote 12, *supra*, $MP_C = E \frac{F}{C}$, which in this case is $.0169/.0209 = .8086$ or about 81%.

²¹ It is worth noting that our approach provides estimates of the marginal product of each input: how much the last dollar of stock or flow added to output. In general, infra-marginal investments have higher rates of return than marginal investments, so the return to the first dollar invested in computers is likely to be even higher than the marginal returns we reported.

²² We thank Dan Sichel for pointing this out.

The above estimates strongly support hypothesis H1, that the contribution of IT is positive. The t-statistics for our estimates of the elasticity of COMPUTER CAPITAL and IS STAFF are 3.92 and 3.38, respectively, so we can reject the null hypothesis of zero contribution of IT at the 0.001 (two-tailed) confidence level for both. We can also reject the joint hypothesis that they are both equal to zero ($\chi^2(2)=43.9$, $p<.0001$).

To assess H2 (that the contribution of IT is greater than its cost) it is necessary to estimate the cost of COMPUTER CAPITAL and IS STAFF. After these costs are subtracted from the gross benefits reported above, we can then assess whether the remaining "net" benefits are positive. Because IS STAFF is a flow variable, calculating net benefits is straightforward: a dollar of IS STAFF costs one dollar, so the gross marginal product of \$2.62 implies a net marginal product of \$1.62. For IS STAFF, we can reject the null hypothesis that the returns equal costs in favor of the hypothesis that returns exceed costs at the .05 confidence level ($\chi^2(1)=4.4$, $p<.035$).

Assessing H2 for COMPUTER CAPITAL, which is a stock variable, requires that we determine how much of the capital stock is "used up" each year and must be replaced just to return to the level at the beginning of the year. This is done by multiplying the annual depreciation²³ rate for computers by the capital stock in place. According to the Bureau of Economic Analysis, the average service life of "Office, Computing and Accounting Machinery" is seven years (Bureau of Economic Analysis 1987). If a seven year service life for computer capital is assumed, then the above gross marginal product should be reduced by subtracting just over 14% per year, so that after seven years the capital stock will be fully replaced. This procedure yields a net marginal of 67%. However, a more conservative assumption is that COMPUTER CAPITAL (in particular PCs) could have an average service life as short as 3 years, which implies that the net rate of return should be reduced by 33%. This would yield a net MP estimate of 48%. In either case, we can reject the null hypothesis that the net marginal returns to computers are zero ($p < .01$).

However, it should be noted that the full cost of computers involves other considerations than just the decline in value of the asset itself. For instance, calculating a Jorgensonian

²³ Technically, "negative capital gains" may be a more accurate term than "depreciation", since computer equipment is more likely to be replaced because of the arrival of cheaper, faster alternatives than because it simply wears out.

cost of capital (Christensen and Jorgenson 1969) would also attempt to account for the effects of taxes, adjustment costs and capital gains or losses, in addition to depreciation costs. On the other hand, firms invest in IT at least partly to move down the learning curve (Brynjolfsson, 1993) or create options (Kambil, Henderson & Mohsenzadeh, 1993), and these effects may create "assets" offsetting some of the losses to depreciation. The high gross marginal product of COMPUTER CAPITAL suggests that if the total annual cost of COMPUTER CAPITAL were as much as 40%, its net marginal product would be greater than zero by a statistically significant amount.

An alternative approach to assessing H2 is to consider the *opportunity cost* of investing in COMPUTER CAPITAL or IS STAFF. A dollar spent in either of these areas could have generated a gross return of over 6% if it had instead been spent on NON-COMPUTER CAPITAL or a net return of 7% if it were spent on OTHER LABOR AND EXPENSE. In this interpretation, there are only excess returns to COMPUTER CAPITAL or IS STAFF if the returns exceed the return of the respective non-IS component.

As shown in Table 6, we can reject the hypothesis that the net MP for COMPUTER CAPITAL is equal to the MP for NON-COMPUTER CAPITAL, assuming a service life of as little as 3 years for COMPUTER CAPITAL (and none in NON-COMPUTER CAPITAL) at the .05 confidence level. Similarly, we can reject the hypothesis that IS STAFF generates the same returns as spending on OTHER LABOR AND EXPENSE ($p < .05$).

Our confidence in the regression taken as a whole is increased by the fact that the estimated output elasticities for the other, non-IT, factors of production were all positive and each was consistent not only with economic theory (i.e. they imply a real rate of return on non-IT factors of 6%-7%), but also with estimates of other researchers working with similar data (e.g. Hall, 1993; Loveman, 1994). Furthermore, the elasticities summed to just over one, implying constant or slightly increasing returns to scale overall, which is consistent with the estimates of aggregate production functions by other researchers (Berndt, 1991). The R^2 hovered around 99%, indicating that our independent variables could "explain" most of the variance in output.

Our results suggest that during the 1987-1991 time period, firms could have created more value if they had spent more on computer capital and labor and less on non-computer

capital and labor than they actually did. In the conclusion section, we discuss some reasons why managers may have made decisions which, with the benefit of hindsight, appear to have been sub-optimal. First, however, we will further analyze the robustness of our results.

3.2 What factors affect the rates of return for computers?

The estimates described above were based on the assumption that the parameters did not vary over time, in different sectors, or across different subsamples of firms. Therefore, they should be interpreted only as overall averages. However, by using the multiple equations approach, it is also possible to address questions like: "Has the return to computers been consistently high, or did it vary over time?" and "Have some sectors of the economy had more success in using computers?" We address these questions by allowing the parameters to vary by year or by sector.

Economic theory predicts that managers will increase investments in any inputs that achieve higher than normal returns, and that as investment increases, marginal rates of return eventually fall to normal levels. This pattern is supported by our findings for COMPUTER CAPITAL, which exhibited higher levels of investment (Figure 2) and lower returns over time (Figure 3). We find that the rates of return are fairly consistent over the period 1987-1989 and then drop in 1990-1991. We can reject the null hypothesis of equality of returns over time in the full sample ($\chi^2(4)=11.2, p<.02$). Nonetheless, even at the end of the period, the returns to COMPUTER CAPITAL still exceed the returns to NON-COMPUTER CAPITAL. However, these results should be interpreted with caution since they are particularly sensitive to sample changes and time-specific exogenous events such as the 1991 recession.²⁴

Roach (1987) has argued that the service sector uses computers much less efficiently than manufacturing and points to aggregate statistics which report higher overall productivity growth for manufacturing than for services. Our data set allows us to reconsider this claim in light of more disaggregated data. The marginal products of COMPUTER CAPITAL across sectors are presented in Figure 4. The marginal product (ignoring the mining sector which

²⁴ A decline in the returns to COMPUTER CAPITAL between 1989 and 1990 is also evident in a balanced panel of 201 firms in the sample for 1989-1991.

includes only 10 firms and has a large standard error) varies from 10% in transportation and utilities to 127% in non-durable manufacturing. While there have been some suggestions that reorganizing service processes around a "factory" model may help services achieve productivity gains comparable to manufacturing, we cannot confirm that the differences in measured returns are due to fundamental differences, or simply "noise" in the data. Although the returns to computers in durable and non-durable manufacturing are as high or higher than the returns in any other sector, we are unable to reject the hypothesis that these rates of return are the same across most sectors due to the imprecision of the estimates (without mining, $\chi^2(4)=6.6$, $p<.16$).

A second area that can be addressed by our data and method is technology strategy. We have already found that firms with more computer capital will, *ceteris paribus*, have higher sales than firms with less computer capital, but do the types of computer equipment purchased make a difference? We have data on two categories of equipment: 1) central processors, such as mainframes, and 2) PCs and terminals. For this analysis, we divide the sample into three equal groups based on the ratio of central processor value to PCs and terminals. We find that the rate of return is highest for firms using a more balanced mix of PCs and mainframes (Table 4), and lower for firms at either extreme. One interpretation of this finding is that an IS strategy which relies too heavily on one category of equipment and users will be less effective than a more even-handed approach which allows a better "division of labor".

3.3 Sensitivity Analysis and Possible Biases - Econometric Issues

Our estimates of the return to COMPUTER CAPITAL required that a number of assumptions be made about the econometric specification and the construction of the data set. This section and the following section explore the validity of our assumptions and generally find that the results are robust.

The econometric assumptions required for ISUR to produce unbiased estimates of both the parameters and the standard errors are similar to those for OLS: the error term must be uncorrelated with the regressors (inputs) and homoskedastic in the cross section.²⁵ ISUR

²⁵ Note that if we had used OLS, further assumptions would be required: that all error terms are independent and constant variance over time.

implicitly corrects for serial correlation and heteroskedasticity over time in our formulation, so that additional restrictions on the error structure are not necessary. Nonetheless, we computed single-year OLS estimates both with and without heteroskedasticity-consistent standard errors to examine whether heteroskedasticity is an issue for the cross-section. The standard error estimates were within 10-20% of each other, indicating that heteroskedasticity does not appear to be a problem. To test normality of the error terms, we computed and plotted residuals from the basic specification, and found them to be roughly normally distributed. It should be noted that even if these assumptions were violated, the coefficient estimates (even for OLS) would still be unbiased and consistent (although the estimated standard error would be incorrect).

However, the assumption that the error term is uncorrelated with the inputs (orthogonality) is potentially an issue. One way in which this assumption could be violated is if the causality is reversed: instead of increases in purchases of inputs (e.g. computers) leading to higher output, an increase in output could lead to further investment (for example, a firm spends the proceeds from an unexpected increase in demand on more computer equipment). In this case, the assumptions for ISUR are violated since the inputs are not predetermined, and therefore the error term is likely to be correlated with them. The orthogonality assumption can also be violated if the input variables are measured with error. The direction of bias of the coefficients from measurement error is dependent on both the correlation between the variables as well as the correlation between measurement errors (see Kmenta (1986) for a complete discussion).²⁶

Regardless of the source of the error, it is possible to correct for the potential bias using instrumental variables methods, or two-stage least squares (2SLS). This method employs instrumental variables to filter out the endogenous variation and error in the variables, which then allows consistent estimation of the parameters. We use once-lagged values of variables as instruments, since by definition they cannot be associated with unanticipated shocks in the dependent variable in the following year.²⁷ Table 5 reports a comparison of pooled OLS estimates with 2SLS estimates and shows that the coefficient estimates are

²⁶ If an input variable is systematically understated by a constant multiplicative factor, then the coefficient estimates would be unchanged.

²⁷ However, in the presence of individual firm effects, lagged values are not valid instruments. While we did not test for firm effects, we suspect they may be important, and so the results of our 2SLS estimates should be interpreted with caution.

similar although somewhat higher for COMPUTER CAPITAL and lower for IS STAFF. In both cases the standard errors were substantially larger, as is expected when instrumental variables are used. Using a Hausman specification test, we cannot reject the null hypothesis that the error term is uncorrelated with the regressors (see bottom of Table 5 for test statistics), and therefore do not reject our initial specification.

3.4 Sensitivity Analysis and Possible Biases - Data Issues

To further explore the robustness of our results, we examined impact of the possible data errors discussed in section 2.3 that can be tested: 1) error in the valuation of PCs and terminals, 2) errors in the price deflators, and 3) understatement or misclassification of computer capital .

To assess the sensitivity of the results to possible errors in the valuation of PCs and terminals, we recalculated the basic regressions varying the assumed average PC and terminal value from \$0 to \$6K. Note that as the assumed value of PCs and terminals increases, the increase in COMPUTER CAPITAL will be matched by an equal decrease in NON-COMPUTER CAPITAL, which is calculated as a residual. Interestingly, as shown in Figure 5, the return to COMPUTER CAPITAL in the basic regression is not very sensitive to the assumed value of PCs and terminals, ranging from 77% if they are not counted to 59% if PCs and terminals are counted at \$6K. The reason the return rises at first when PCs and terminals are counted as part of COMPUTER CAPITAL is presumably that firms with large investments in PCs and terminals have higher output than similar firms without such investments. Initially, this increased output raises the estimated elasticity of COMPUTER CAPITAL (the numerator of MP) by more than the assumed costs of PCs and terminals (the denominator), and therefore the estimated return to computers increases.

A second contribution to error is the understatement of output due to errors in the price deflators. While it is difficult to directly correct for this problem, we estimated the basic equations year by year, so that errors in the relative deflators would have no impact on the elasticity estimates. The estimated marginal products ranged from 109% to 197% in the individual year regressions versus 81% when all five years were estimated simultaneously. The standard error on the estimates was significantly higher for all estimates, which can account for the greater range of estimates. Overall, this suggests that our basic findings are

not a result of the assumed price deflators. However, if the price deflators systematically underestimate the value of intangible product change over time or between firms, our measure of output will be understated, implying that the actual return for computer capital is higher than our estimates.

To assess the third source of error, possible understatement or misclassification of computer capital, we consider three cases: 1) hidden computer spending exists, but does not show up elsewhere in the data, 2) hidden computer spending exists and shows up in the "NON-IS LABOR AND EXPENSE" category, or 3) hidden computer spending exists and shows up in the "OTHER CAPITAL" category. If the hidden IS costs do not show up elsewhere in the firm (e.g. software development or training costs from previous years), then the effect on the estimated returns is dependent on how closely correlated these costs are to our measured COMPUTER CAPITAL. If they are uncorrelated, our estimate for the elasticity and the return to COMPUTER CAPITAL is unbiased. If the missing costs are perfectly correlated with the observed costs, then, because of the logarithmic form of our specification, they will result only in a multiplicative scaling of the variables, and the estimated elasticities and the estimated standard error will be unchanged.²⁸ For the same reason, the sign and statistical significance of our results for the returns to COMPUTER CAPITAL and IS STAFF will also be unaffected. However, the denominator used for the MP calculations will be affected by increasing computer capital so the estimated MP will be proportionately lower or higher. For instance, if the hidden costs lead to a doubling of the true costs of computer capital, then the true MP would fall from 81% to just over 40%. Finally, if the hidden costs are negatively correlated with the observed costs, then the true returns would be higher than our estimates.

A second possible case is that hidden IS capital expenses (e.g. software) show up in the NON-IS LABOR AND EXPENSE category. To estimate the potential impact of these omissions, we estimate the potential size of the omitted misclassified IS capital relative to COMPUTER CAPITAL using data from another IDG survey (IDC 1991) on aggregate IS expenditures, including software as well as hardware. To derive a reasonable lower bound on the returns to COMPUTER CAPITAL, we assume that the misclassified IS capital had an

²⁸ This is because multiplicative scaling of a regressor in a logarithmic specification will not change the coefficient estimate or the standard error. All the influence of the multiplier will appear in the intercept term which is not crucial to our analysis.

average service life of three years, and further make the worst-case assumption of perfect correlation between misclassified IS capital and COMPUTER CAPITAL (and reduce proportionally the amount of NON-IS LABOR AND EXPENSE). In this scenario, our estimates for the amount of COMPUTER CAPITAL in firms roughly doubles, yet the rates of return are little unchanged from the basic analysis that does not include misclassified IS capital (68% vs. 81%). This surprising result appears to be due to the fact that the return on NON-IS LABOR AND EXPENSE is at least as high as the return on COMPUTER CAPITAL, so moving costs from one category to another does not change overall returns much.

Alternatively, a third possible case is that the hidden IS capital expenditures show up in OTHER CAPITAL. This would apply to items such as telecommunications hardware which would normally be classified as a capital expenditure. In this case, the marginal product of COMPUTER CAPITAL will be reduced proportionally to the amount of the misclassification. Intuitively, this case is similar to the case discussed earlier in which the hidden costs are perfectly correlated with measured costs but do not appear elsewhere. To confirm this result, we recalculated the regression assuming that missing capital costs were as much as 100% the amount of measured computer capital under the worst-case assumption that the misclassified capital was perfectly correlated with the measured capital. The elasticities for both capital components change less than 5% as the amount of misclassified capital was varied.

Irrespective of these sensitivity calculations, it should be noted that the definition of COMPUTER CAPITAL used in this study was fairly narrow and did not include items such as telecommunications equipment, scientific instruments, or networking equipment. The findings should be interpreted accordingly and do not necessarily apply to broader definitions of IT. However, to the extent that the assumptions of our sensitivity analysis hold, the general finding that IT contributes significantly to output is robust (H1), although the actual point estimates of marginal product may vary. Depending on the magnitude of the error and the assumed cost of computer capital, mismeasurement could lead to the conclusion that there are no differences in net marginal product between computer capital and other capital.

On balance, we may have underestimated both IS input and final output. The directions of the resulting biases go in opposite directions, but under reasonable assumptions they do not

appear to obviate the basic finding that the return on IS capital and labor spending is statistically significant and exceeds that of other types of capital and labor.

4. DISCUSSION

4.1 Comparison with earlier research

Although we found that computer capital and IS labor increase output significantly under a variety of formulations (see summary table 7), several other studies have failed to find evidence that IT increases output. Because the models we used were similar to those used by several previous researchers, we attribute our different findings primarily to the larger and more recent data set we used. Specifically, there are at least three reasons why our results may differ from previous results.

First, we examined a later time period, (1987-1991), than did Loveman (1978-1982), Barua et al. (1978-1982) or Berndt & Morrison (1968-1986). The massive build-up of computer capital is a relatively recent phenomenon. Indeed, the delivered amount of computer power in the companies in our sample is likely to be at least an order of magnitude greater than that in comparable firms from the period studied by the other authors. Brynjolfsson (1993) argues that even if the MP of IT were twice that of non-IT capital, its impact on output in the 1970s or early 1980s would not have been large enough to be detected with available data by conventional estimation procedures. Furthermore, the changes in business processes needed to realize the benefits of IT may have taken some time to implement, so it is possible that the actual returns from investments in computers were initially fairly low. In particular, computers may have initially created organizational slack which was only recently eliminated, perhaps hastened by the increased attention engendered by earlier studies that indicated a potential productivity shortfall and suggestions that "to computerize the office, you have to reinvent the office" (Thurow 1990). Apparently, an analogous period of organizational redesign was necessary to unleash the benefits of electric motors (David, 1989).

A pattern of low initial returns is also consistent with the strategy for optimal investment in the presence of learning-by-using: short-term returns should initially be lower than returns for other capital, but subsequently rise to exceed the returns to other capital, compensating

for the "investment" in learning (Lester & McCabe, 1993). Under this interpretation, our high estimates of computer MP indicate that businesses are beginning to reap rewards from the experimentation and learning phase in the early 1980s.

Second, we were able to use different and more detailed firm-level data than had been available before. We argue that the effects of computers in increasing variety, quality or other intangibles are more likely to be detected in firm level data than in the aggregate data. Unfortunately, all such data, including ours, is likely to include data errors. It is possible that the data errors in our sample happened to be more favorable (or less unfavorable) to computers than those in other samples. We attempted to minimize the influence of data errors by cross-checking with other data sources, eliminating outliers, and examining the robustness of the results to different subsamples and specifications. In addition, the large size of our sample, should, by the law of large numbers, mitigate the influence of random disturbances. Indeed, the precision of our estimates was generally much higher than those of previous studies; the statistical significance of our estimates owes as much to the tighter confidence bounds as to higher point estimates.

Third, our sample consisted entirely of relatively large "Fortune 500" firms. It is possible that the high IS contribution we find is limited to these larger firms. However, an earlier study, [(Brynjolfsson *et al.* 1994)], found evidence that smaller firms may benefit disproportionately from investments in information technology. In any event, because firms in the sample accounted for a large share of the total US output, the economic relevance of our findings is not heavily dependent on extrapolation of the results to firms outside of the sample.

4.2 Managerial Implications

If the spending on computers is correlated with significantly higher returns than spending on other types of capital, it does not necessarily follow that companies should increase spending on computers. The firms with high returns and high levels of computer investment may differ systematically from the low performers in ways that cannot be rectified simply by increasing spending. For instance, recent economic theory has suggested that "modern manufacturing", involving high intensity of computer usage, may require a radical change in organization (Milgrom & Roberts, 1990). This possibility is

emphasized in numerous management books and articles (see, e.g. Malone & Rockart, 1991; Scott Morton, 1991) and supported in our discussions with managers, both at their firms and during a workshop on IT and Productivity attended by approximately 30 industry representatives.²⁹

Furthermore, our results showing a high gross marginal product may be indicative of the differences between computer investment and other types of investment. For instance, managers may perceive IS investment as riskier than other investments, and therefore require higher expected returns to compensate for the increased risk. Finally, IS is often cited as an enabling technology which does not just produce productivity improvements for individuals, but provides benefits by facilitating business process redesign or improving the ability of groups to work together. In this sense, our results may be indicative of the substantial payoffs to reengineering and other recent business innovations.

5. CONCLUSION

We examined data which included over 1000 observations on output and several inputs at the firm level for 1987-1991. The firms in our sample had aggregate sales of over \$1.8 trillion in 1991 and thus account for a substantial share of the U.S. economy. We tested a broad variety of specifications, examined several different subsamples of the data, and validated the assumptions of our econometric procedures to the extent possible.

The data indicate that COMPUTER CAPITAL and IS STAFF spending contribute significantly to firm level OUTPUT. Furthermore, we were able to reject the hypothesis that the (gross) MP for COMPUTER CAPITAL was equal to the MP for NON-COMPUTER CAPITAL in favor of the hypothesis that the MP for COMPUTER CAPITAL was higher. When we adjusted for depreciation using the BEA 7-year service life assumption for COMPUTER CAPITAL, the differences in marginal product are still significant, suggesting the possibility of excess returns to computer spending. The basic result that COMPUTER CAPITAL and IS STAFF contribute significantly to total output are robust to reasonable assumptions about measurement error due to exclusion of unmeasured factors. However, the evidence of excess returns is not as strong, and the null hypothesis that there are no excess returns to

²⁹ The MIT Center for Coordination Science and International Financial Services Research Center jointly sponsored a Workshop on IT and Productivity which was held in December, 1992.

COMPUTER CAPITAL cannot be rejected if we assume that there are significant unmeasured costs to computer spending.

There are a number of other directions in which this work could be extended. In the current formulation, it is difficult to make direct comparisons between firms in different industries because the definitions of "output" vary. An alternative dependent variable which can be estimated using production functions is value added. This approach should treat firms in a more comparable way, allowing greater precision in estimating the effects of IS spending, and therefore enabling more complex production function relationships to be examined. It would also be worthwhile to investigate the role of other variables, such as research and development expenditures, which might be associated with the advancement of technology in general, and IT in particular. One recent study (Dunne, 1993) suggested that firms which invest heavily in R&D are also most innovative in their use of IT.

Although our approach allowed us to infer the value created by intangibles like product variety by looking at changes in the revenues at the firm level, more direct approaches might also be promising. For instance, other variables can be collected to see whether computer productivity is systematically related to characteristics such as variety of product line, or the average defect rate in their output.

Finally, the type of extension which is likely to have the greatest impact on practice is further analysis of the factors which differentiate firms with high returns to IT from low performers. For instance, is the current "downsizing" of firms leading to higher IT productivity? Are the firms that have undertaken substantial "reengineering efforts" also the ones with the highest returns? Since this study has presented evidence that the computer "productivity paradox" is a thing of the past, it seems appropriate that the next round of work should focus on identifying the strategies which have led to large IT productivity.

5. TABLES AND FIGURES

Figure 1: Comparison of Gross Marginal Product

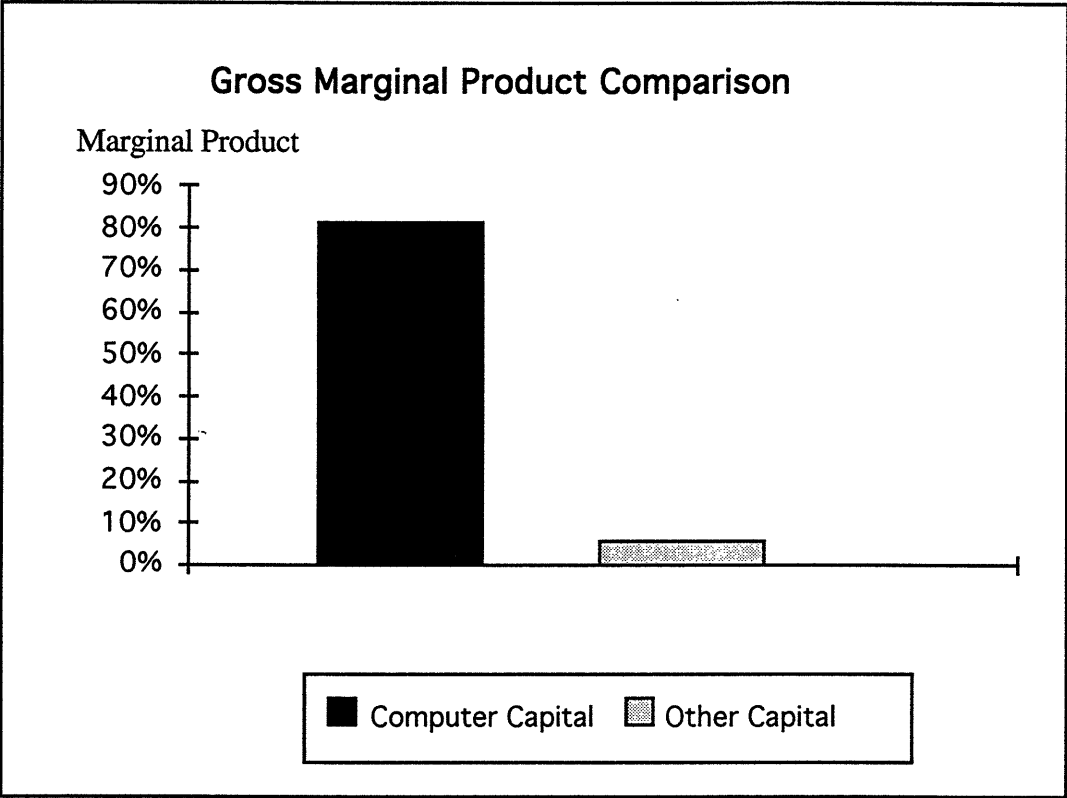


Figure 2: Changes in IT Inputs over Time

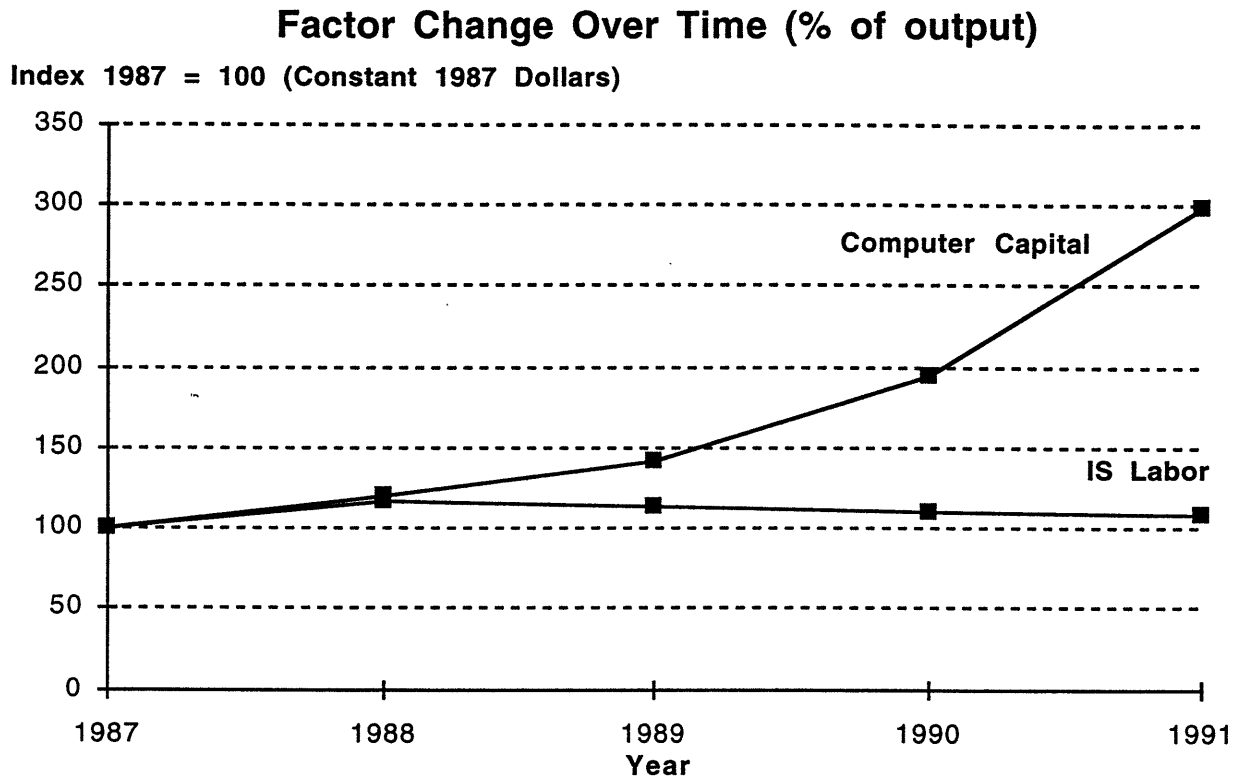
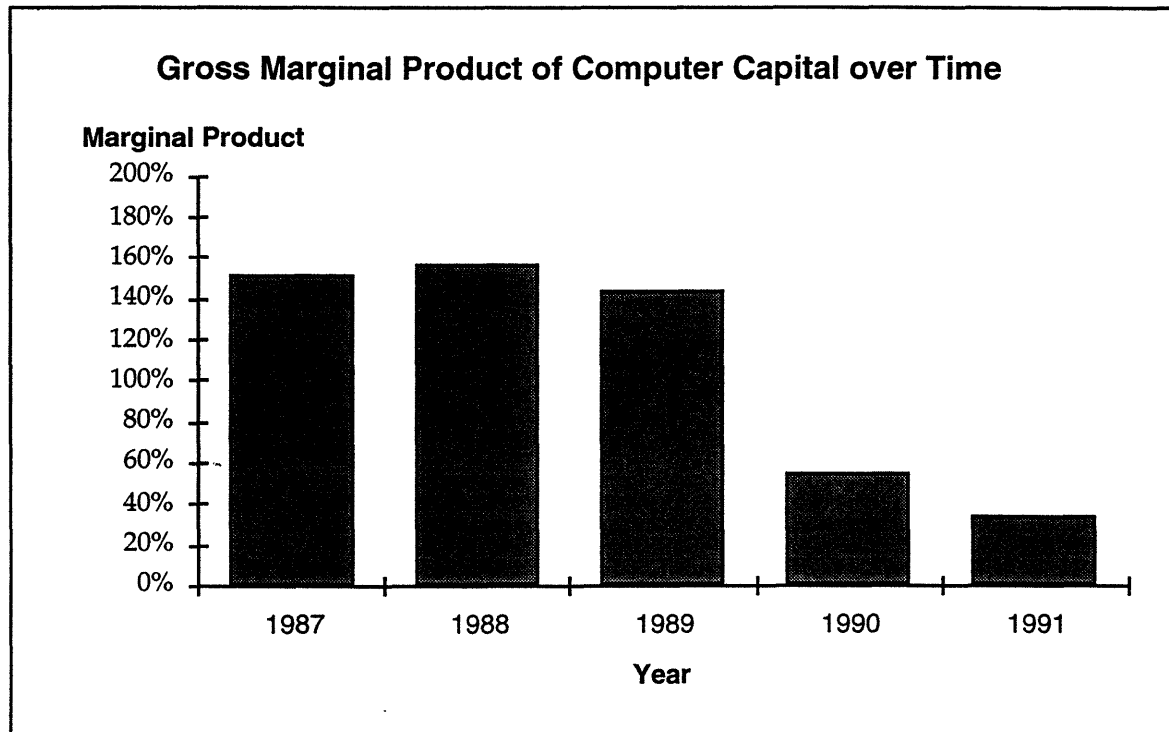


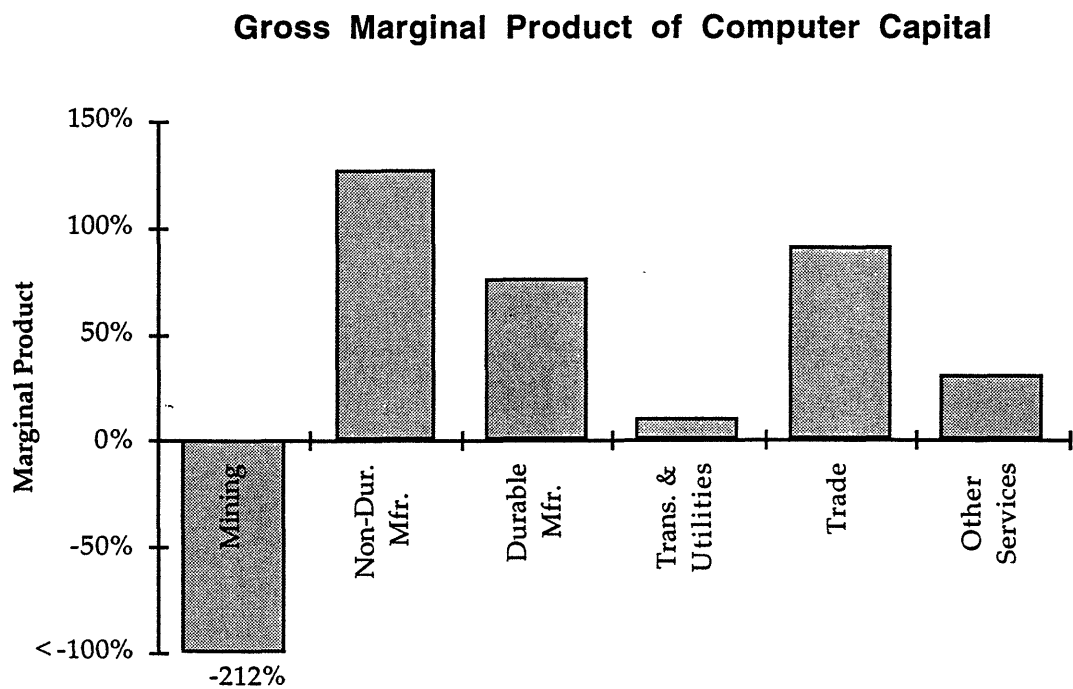
Figure 3: Gross Marginal Product of Computer Capital over Time



	1987	1988	1989	1990	1991
Coefficient	.0177**	.0222***	.0239***	.0125**	.0121**
Std. Error	(.00721)	(.00646)	(.00657)	(.00574)	(.00594)
N	135	133	274	286	293

Key: *** - $p < .01$, ** - $p < .05$, * - $p < .1$, standard errors in parenthesis

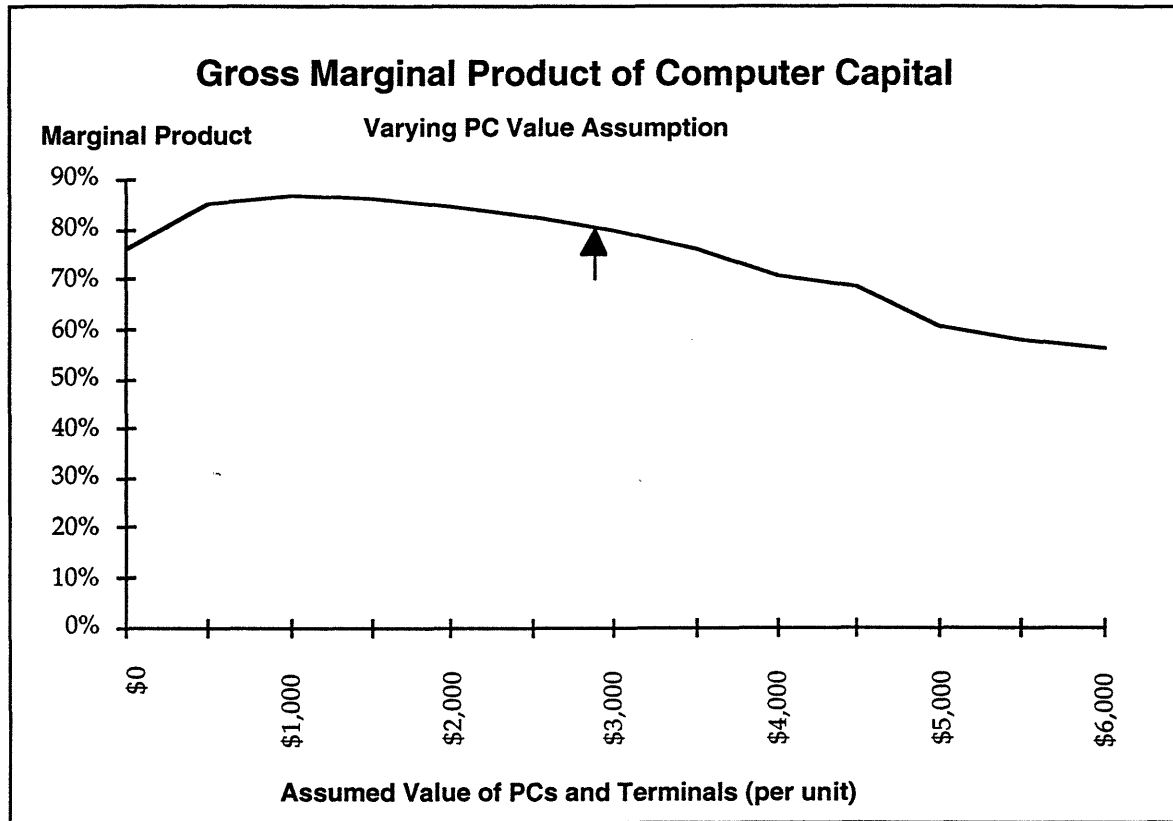
Figure 4: Gross Marginal Product of Computer Capital by Sector



	Mining	Non-Dur. Mfr.	Durable Mfr.	Trans. & Utilities	Trade	Other Service
Coefficient	-.0286	.0122*	.0348***	.00227	.0129	.0153
Std. Error	(.0218)	(.00691)	(.00678)	(.0111)	(.00921)	(.0354)
N (total)	28	414	360	171	123	25

Key: *** - $p < .01$, ** - $p < .05$, * - $p < .1$, standard errors in parenthesis

Figure 5: Gross Marginal Product for Computer Capital with different PC value assumptions



Note: Other parameter estimates and regression statistics are very close to the values shown in table 3, column 1 for all regressions.

Table 1: Data Sources, Construction Procedures, and Deflators

Series	Source	Construction Procedure	Deflator
Computer Capital	IDG Survey	"Market Value of Central Processors" converted to constant 1987 dollars, plus the total number of PCs and terminals multiplied by an average value of a PC/terminal, also converted to constant 1987 dollars.	Deflator for Computer Systems (Gordon, 1993). Extended through 1991 at a constant rate.
Non-Computer Capital	Compustat	Total Property, Plant and Equipment Investment converted to constant 1987 dollars. Adjusted for retirements using Winfrey S-3 Table (10 year service life) and aggregated to create capital stock. Computer capital as calculated above was subtracted from this result.	GDP Implicit Deflator for Fixed Investment (Council of Economic Advisors, 1992).
IS Staff	IDG Survey	Total IS Budget times percentage of IS Budget (by company) devoted to labor expense. Converted to constant 1987 dollars.	Index of Total Compensation Cost (Private Sector) (Council of Economic Advisors, 1992).
Non-IS Labor and Expense	Compustat	Total Labor, Materials and other non-interest expenses converted to constant 1987 dollars. IS labor as calculated above was subtracted from this result.	Producer Price Index for Intermediate Materials, Supplies and Components (Council of Economic Advisors, 1992).
Output	Compustat	Total sales converted to constant 1987 dollars.	Industry Specific Deflators from <i>Gross Output and Related Series by Industry, BEA (1977-89)</i> where available (about 80% coverage) - extrapolated for 1991 assuming average inflation rate from previous five years. Otherwise, sector level Producer Price Index for Intermediate Materials Supplies and Components (Gorman, 1992).

Table 2a: Summary Statistics

Sample Statistics - Average over all points (Constant 1987 Dollars)			
	Total \$ (Annual Average)	As a % of Output	Per Firm Average
Output	\$1,661Bn	100%	\$7.41 Bn
Computer Capital (stock)	\$34.7 Bn	2.09%	\$155 MM
Non-Computer Capital (stock)	\$1,614 Bn	97.2%	\$7.20 Bn
IS Budget (flow)	\$27.1 Bn	1.63%	\$121 MM
IS Staff (flow)	\$11.3 Bn	0.68%	\$50.4 MM
Non-IS Labor and Expenses (flow)	\$1,384 Bn	83.3%	\$6.17 Bn
Avg. Number of Companies per Year	224	224	224
Total Observations	1121	1121	1121

Table 2b. Sample Composition relative to Fortune 500 Population

Sample Composition Number of firms			
	Fortune 500 Manufacturing	Fortune 500 Service	Other
<u>1991 Sample Breakdown</u>			
Top Half Fortune 500	157	61	
Lower Half Fortune 500	39	22	
Total	196	83	14
<u>All Fortune 500 Firms in Compustat</u>			
Top Half Fortune 500	240	228	
Lower Half Fortune 500	226	196	n.a.
Total	466	424	

Table 3: Base Regressions - Coefficient Estimates and Implied Gross Rates of Return

All parameters (except year dummy) constrained to be equal across years.

Parameter	Coefficients	Marginal Product
β_1 (Computer Capital)	.0169*** (.00431)	81.0%
β_2 (Non-computer Capital)	.0608*** (.00466)	6.26%
β_3 (IS Staff)	.0178*** (.00526)	2.62
β_4 (Other Labor & Exp.)	.883*** (.00724)	1.07
Dummy Variables	Year*** & Sector***	
R ² (1991)	97.5%	
N (1991)	293	
N (total)	1121	

Key: *** - p<.01, ** - p<.05, * - p<.1, standard errors in parenthesis

Table 4: Split Sample Regression Results - Mainframes as a percentage of total Computer Capital

Coefficient Estimates and Marginal Product for Computer Capital				
Grouping based on mainframes as a percentage of total Computer Capital				
Sample Split	Highest	Middle	Lowest	Statistical Ordering ¹
Elasticity Estimate (β_1)	.0113**	.0159***	.0117**	Med>(High,Low) (p<.03)
Standard Error	(.00500)	(.00528)	(.00521)	
Marginal Product (MP _c)	49.1%	79.5%	58.2%	
Mean % Mainframes	74%	54%	34%	
Group Std. Dev.	9%	5%	8%	

Key: *** - p<.01, ** - p<.05, * - p<.1, standard errors in parenthesis

1 - Ordering by χ^2 tests of return differences. P-value shown represents null hypothesis of equality across groups.

Table 5: Specification Test - Comparison of OLS and Two-Stage Least Squares
All parameters (except year dummy) constrained to be equal across years.

Parameter	OLS Estimates	2SLS Estimates
β_1 (Computer Capital)	.0284*** (.00723)	.0435*** (.0126)
β_2 (Non-computer Capital)	.0489*** (.00668)	.0481*** (.00702)
β_3 (IS Staff)	.0191*** (.00795)	.00727 (.0116)
β_4 (Non-IS Labor & Exp.)	.881*** (.0113)	.879*** (.0125)
Dummy Variables	Year*** & Sector***	Year*** & Sector***
R ²	98.3%	98.3%
N (total)	702	702

Key: *** - $p < .01$, ** - $p < .05$, * - $p < .1$, standard errors are in parentheses

Note: OLS estimates are for sample of same firms as were available for 2SLS regression (n=702).

Hausman Test Results (instruments are lagged independent variables):

$\chi^2(4) = 6.40$, ($p < .17$) - cannot reject exogeneity

Table 6: χ^2 Tests for Differences in Marginal Product between Computer Capital and Other Capital

Return Difference Tests Computer Capital vs. Other Capital	Return	χ^2 Statistic	Significance
Gross Return	81%	15.5	p<.001
Net - 7 Year Service Life	67%	10.6	p<.01
Net - 3 Year Service Life	48%	5.5	p<.02

A significant test indicates that the return on computer capital is greater than the return on other capital.

Table 7: Summary of Hypothesis Tests

Hypothesis	Description of Test (alternative hypothesis)	Test Statistic
H1	Positive marginal product for COMPUTER CAPITAL	$t=3.92, p<.01$
H1	Positive marginal product for IS STAFF	$t=3.38, p<.01$
H1	Simultaneous test for positive marginal product for COMPUTER CAPITAL and IS STAFF	$\chi^2(2)=43.9, p<.01$
H2	Positive net marginal product for COMPUTER CAPITAL (see table 6), cost @ 14% (7-year average life)	$t=3.24, p<.01$
H2	Positive net marginal product for COMPUTER CAPITAL (see table 6), cost @ 33% (3-year average life)	$t=2.32, p<.05$
H2	Positive net marginal product for IS STAFF	$\chi^2(1)=4.4, p<.05$
H2	Marginal product of COMPUTER CAPITAL exceeds marginal product of OTHER CAPITAL	see table 6
H2	Marginal product of IS STAFF exceeds marginal product of OTHER LABOR AND EXPENSE	$\chi^2(1)=4.0, p<.05$
Extension of H1	Marginal Product of COMPUTER CAPITAL changes across time	$\chi^2(4)=11.2, p<.02$
Extension of H1	Marginal Product of COMPUTER CAPITAL varies across sectors	$\chi^2(4)=6.6, p<.2$
Extension of H1	Marginal Product varies by mainframes as a percentage of total COMPUTER CAPITAL	$\chi^2(2)=6.9, p<.03$

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